Title: What are the costs of dealing with "states of reality" in quantum theory?

Date: Sep 28, 2009 11:00 AM

URL: http://pirsa.org/09090084

Abstract: Bell and experimental tests of his inequality showed that it is impossible to explain all of the predictions of quantum mechanics using a theory which satisfies the basic concepts of locality and realism, but which (if not both) is violated is still an open question. As it seems impossible to resolve this question experimentally, one can ask how plausible realism -- the idea that external properties of systems exist prior to and independent of observations -- is, by considering the amount of resources consumed by itself and its non-local features. I will construct an explicit realistic model in which the number of hidden-variable states scales polynomially with the number of possible quantum measurements. In the limit of a large number of measurements, the model recovers the result of Montina, that no hidden-variable theory that agrees with quantum predictions could use less hidden-variable states than the straightforward model in which every quantum state is associated with one such hidden state. Thus, for any given system size, realistic theories cannot describe nature more efficiently than quantum theory itself. I will then turn to the problem of "non-locality" in realistic theories showing that every such theory that agrees with quantum predictions allows superluminal signaling at the level of hidden variable states.

universität wien IQOQI

Faculty of Physics, University of Vienna
& Institute of Quantum Optics and Quantum Information (IQOQI)

What are the costs of dealing with „states of reality“ in quantum theory?

Časlav Brukner

with Borivoje Dakic, Johannes Kofler, Tomasz Paterek,
Marcin Pawlowski, Milovan Suvakov

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Microsoft PowerPoint - [Brukner Perimeter 2.ppt]

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

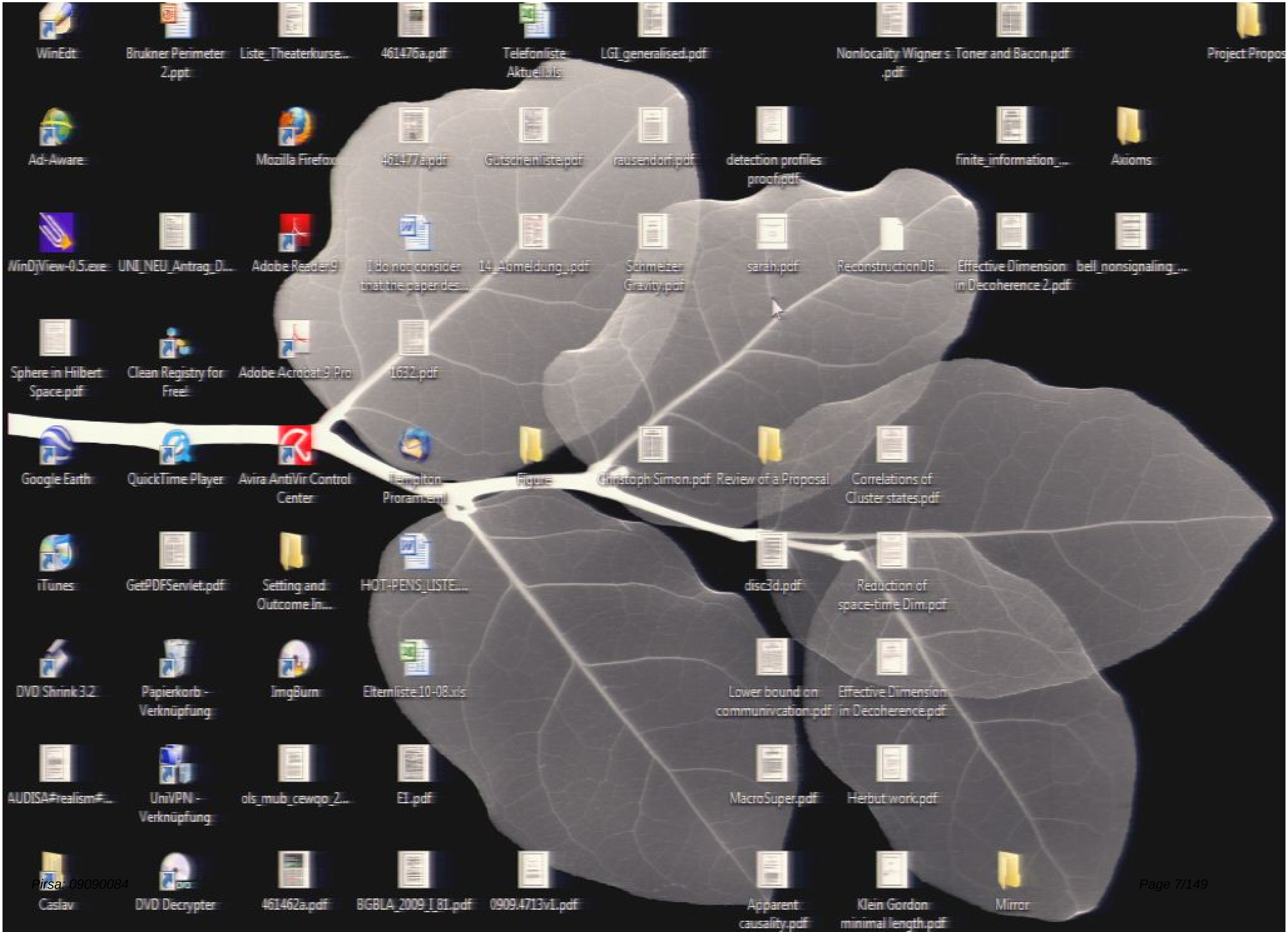
„... no question of mechanical disturbance of the system ...“

„... the question of an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system.“

„Truth and clarity are complementary.“

As quoted in Quantum Theory and the Flight from Realism: Philosophical Responses to Quantum Mechanics (2000) by Christopher Norris, p. 234

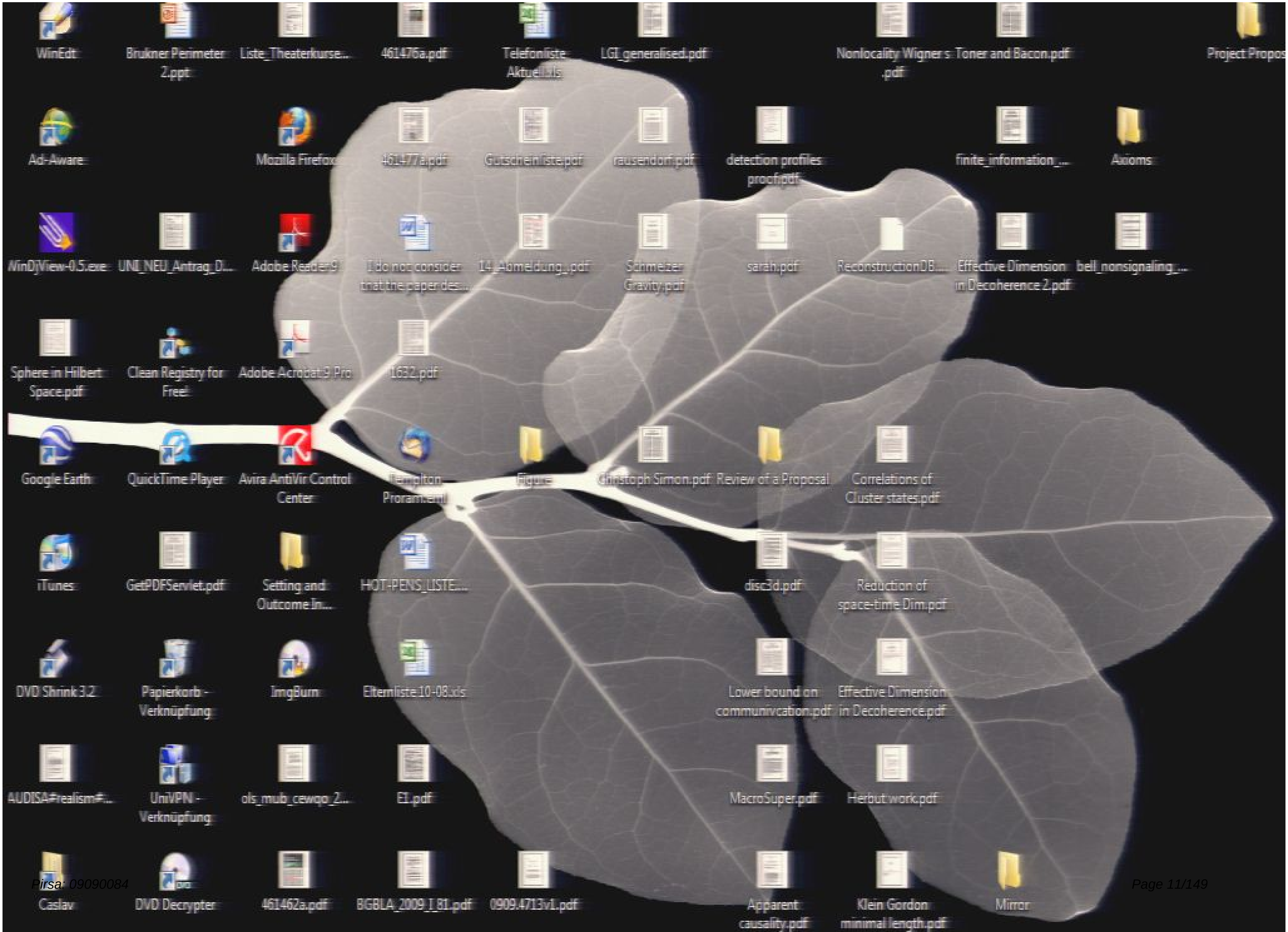
Klicken Sie, um Notizen hinzuzufügen


WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
rausendorf.pdf
detection profiles proof.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Abmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE....
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
AUDISA#realism#...
UniVPN - Verknüpfung
ols_mub_cewqo_2...
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror


WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner's .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
rausendorf.pdf
detection profiles proof.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Abmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE....
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
AUDISA#realism#...
UniVPN - Verknüpfung
ols_mub_cewqo_2...
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror


WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
rausendorf.pdf
detection profiles proof.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Anmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Templeton Proram.eml
Figure
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE....
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Microsoft PowerPoint - [Brukner Perimeter 2.ppt]
Caslav
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror


WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
detection profiles proof.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Abmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB...
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Figure
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE...
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
AUDISA#realism#...
UniVPN - Verknüpfung
ols_mub_cewqo_2...
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror


WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
rausendorf.pdf
detection profiles proof.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Abmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE....
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
AUDISA#realism#...
UniVPN - Verknüpfung
ols_mub_cewqo_2...
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror

Microsoft PowerPoint - [Brukner Perimeter 2.ppt]

Datei Bearbeiten Ansicht Einfügen Format Extras Bildschirmpräsentation Fenster ? Adobe PDF

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

„... no question of mechanical disturbance of the system ...“

„... the question of an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system.“

„Truth and clarity are complementary.“

As quoted in Quantum Theory and the Flight from Realism: Philosophical Responses to Quantum Mechanics (2000) by Christopher Norris, p. 234

Klicken Sie, um Notizen hinzuzufügen

Microsoft PowerPoint - [Brukner Perimeter 2.ppt]

Datei Bearbeiten Ansicht Einfügen Format Extras Bildschirmpräsentation Fenster ? Adobe PDF

Speichern unter...
Drucken... Strg+P
1 Brukner Perimeter 2.ppt
2 F:\Brukner What are the costs.pp...
3 Brukner What are the costs.ppt
4 Figure.ppt

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

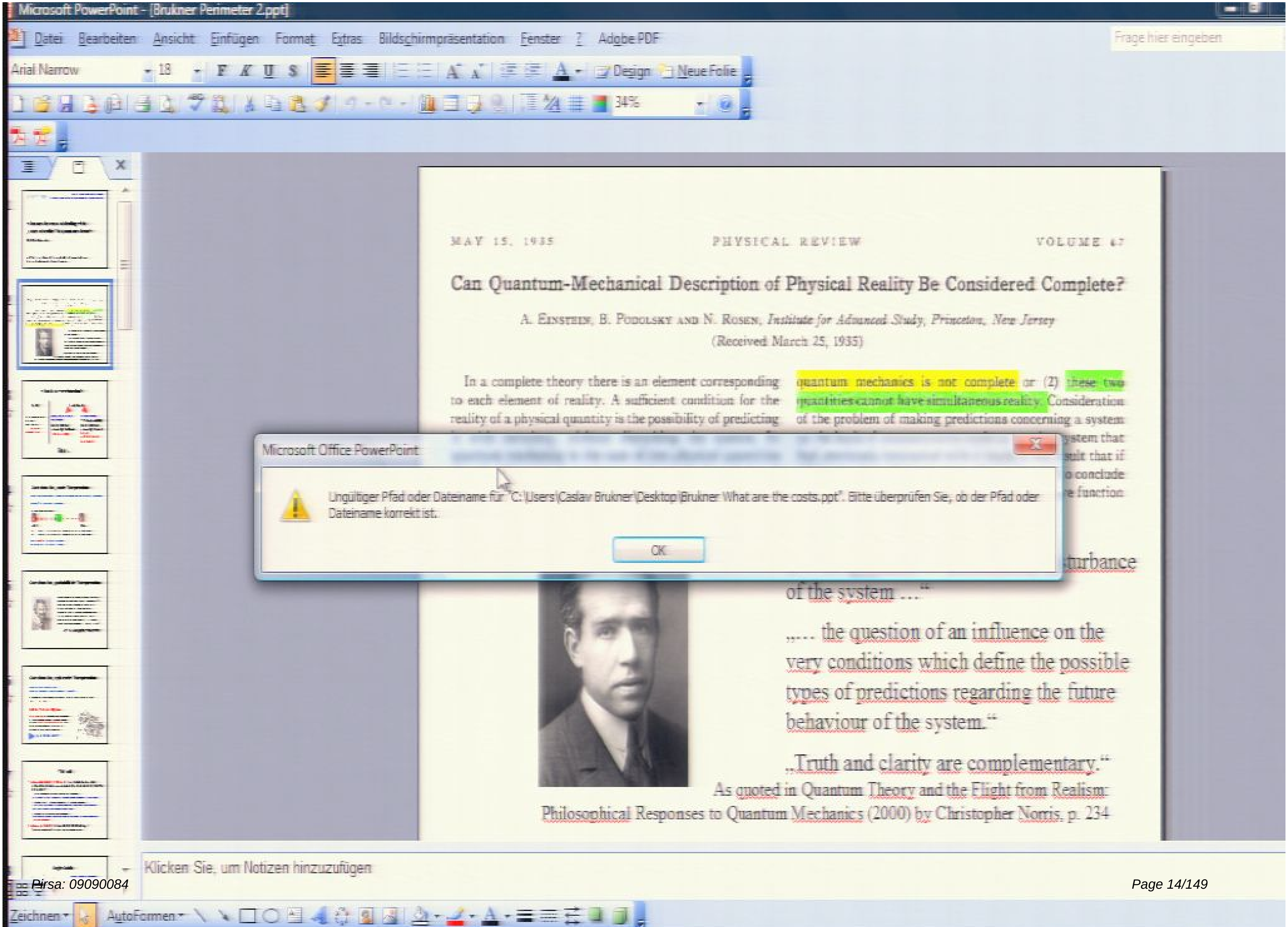
„… no question of mechanical disturbance of the system …“

„… the question of an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system.“

„Truth and clarity are complementary.“

As quoted in Quantum Theory and the Flight from Realism: Philosophical Responses to Quantum Mechanics (2000) by Christopher Norris, p. 234

Klicken Sie, um Notizen hinzuzufügen


Microsoft PowerPoint - [Brukner Perimeter 2.ppt]
Datei Bearbeiten Ansicht Einfügen Format Extras Bildschirmpräsentation Fenster ? Adobe PDF
Frage hier eingeben
Arial Narrow 18
Design Neue Folie
34%
MAY 15, 1935 PHYSICAL REVIEW VOLUME 47
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?
A. Einstein, B. Podolsky and N. Rosen, Institute for Advanced Study, Princeton, New Jersey
(Received March 25, 1935)
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting
quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system
Microsoft Office PowerPoint
Ungültiger Pfad oder Dateiname für "C:\Users\Caslav Brukner\Desktop\Brukner What are the costs.ppt". Bitte überprüfen Sie, ob der Pfad oder Dateiname korrekt ist.
OK
of the system ...“
„... the question of an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system.“
„Truth and clarity are complementary.“
As quoted in Quantum Theory and the Flight from Realism: Philosophical Responses to Quantum Mechanics (2000) by Christopher Norris, p. 234
Klicken Sie, um Notizen hinzuzufügen
Zeichnen AutoFormen

Microsoft PowerPoint - [Brukner Perimeter 2.ppt]

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

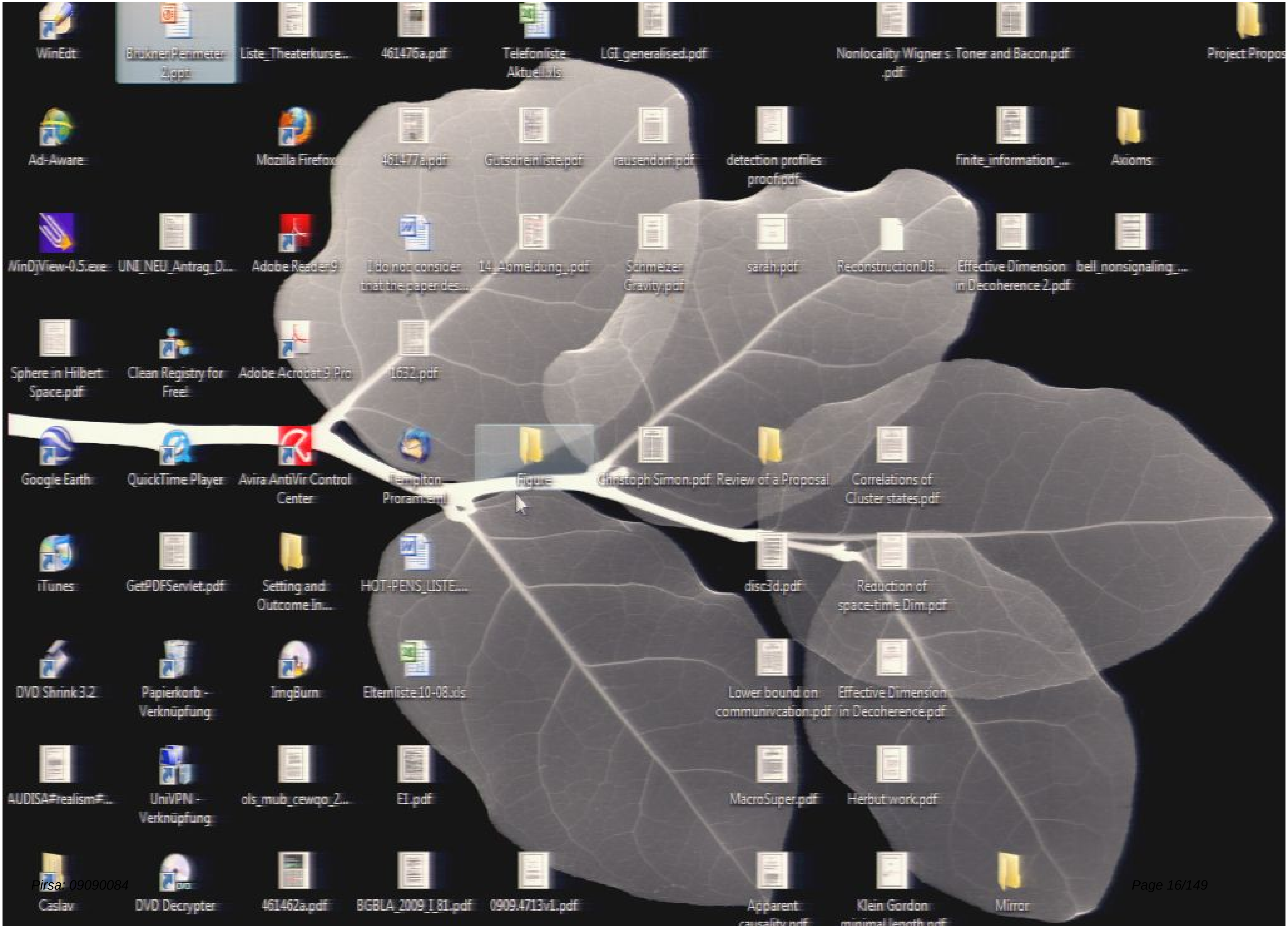
„… no question of mechanical disturbance of the system …"

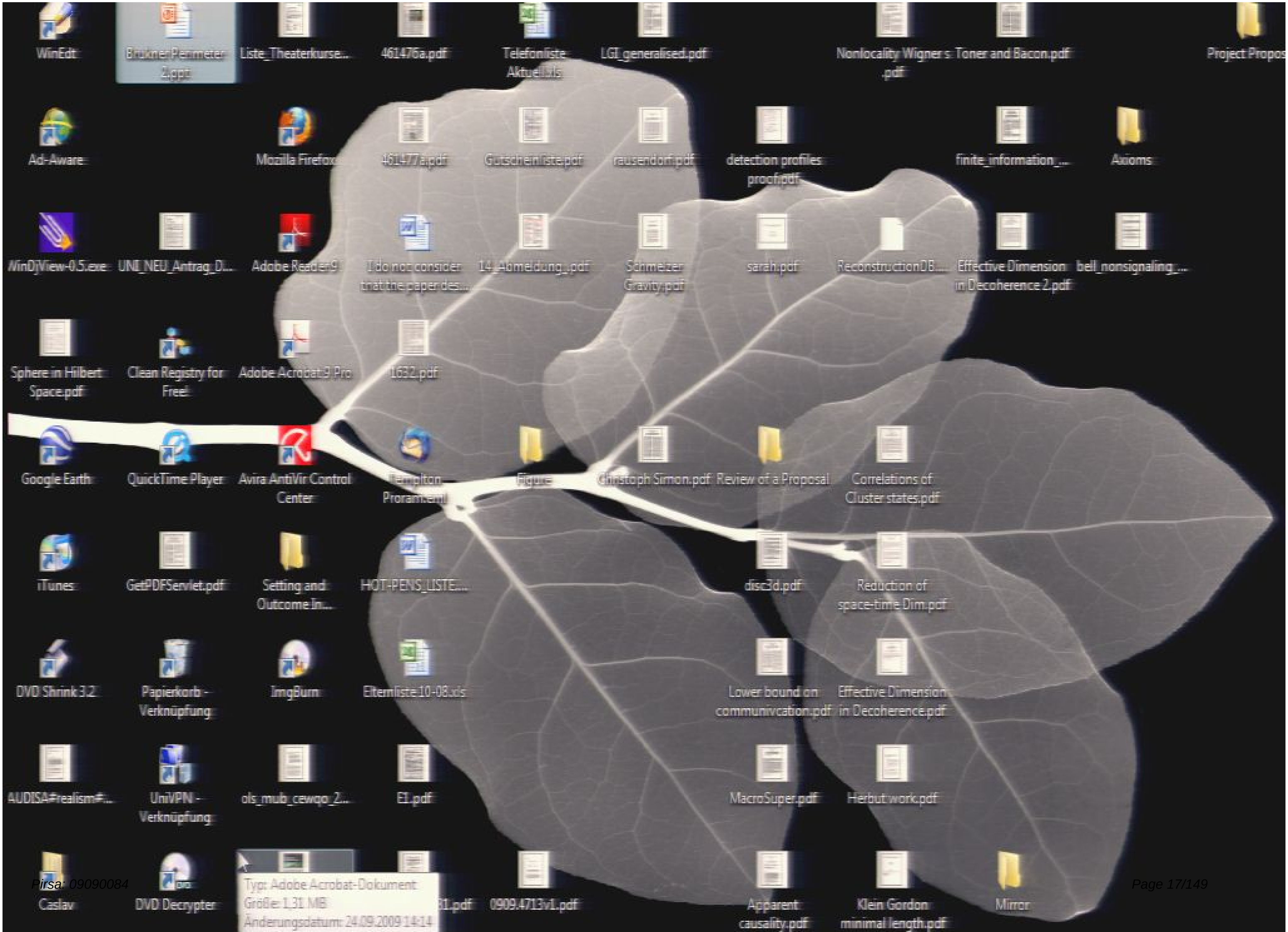
„… the question of an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system."

„Truth and clarity are complementary."

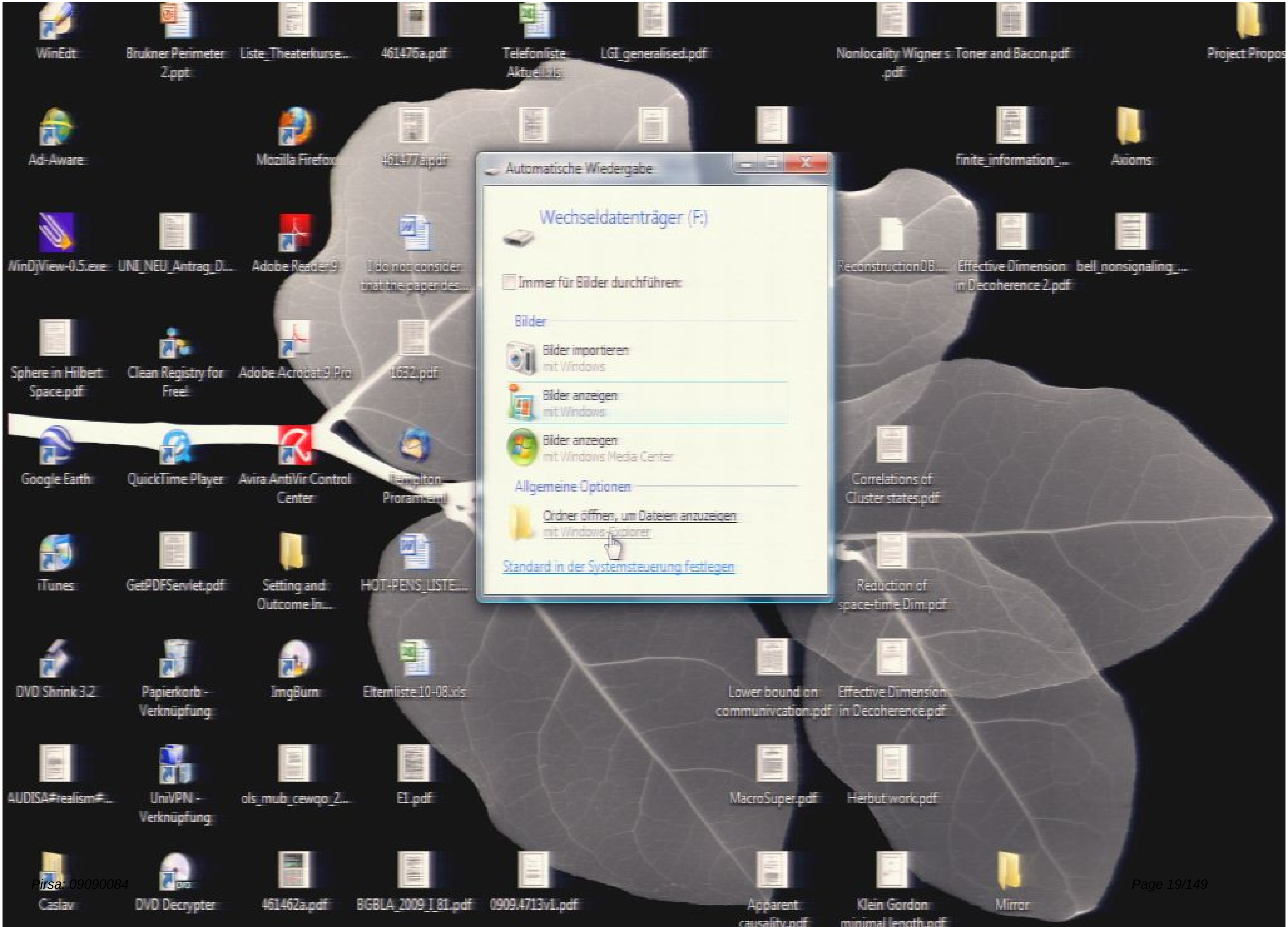
As quoted in Quantum Theory and the Flight from Realism: Philosophical Responses to Quantum Mechanics (2000) by Christopher Norris, p. 234

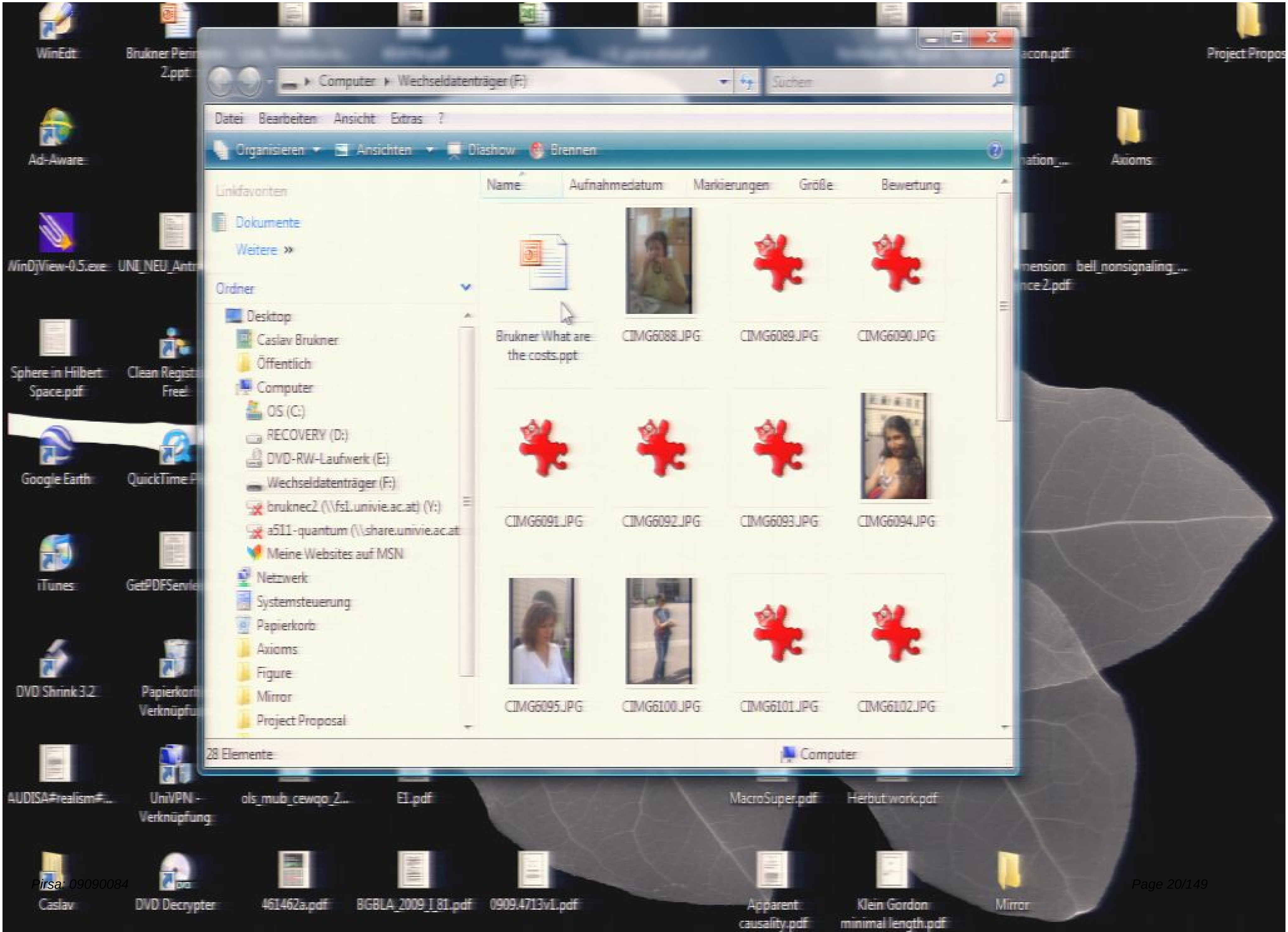
Klicken Sie, um Notizen hinzuzufügen

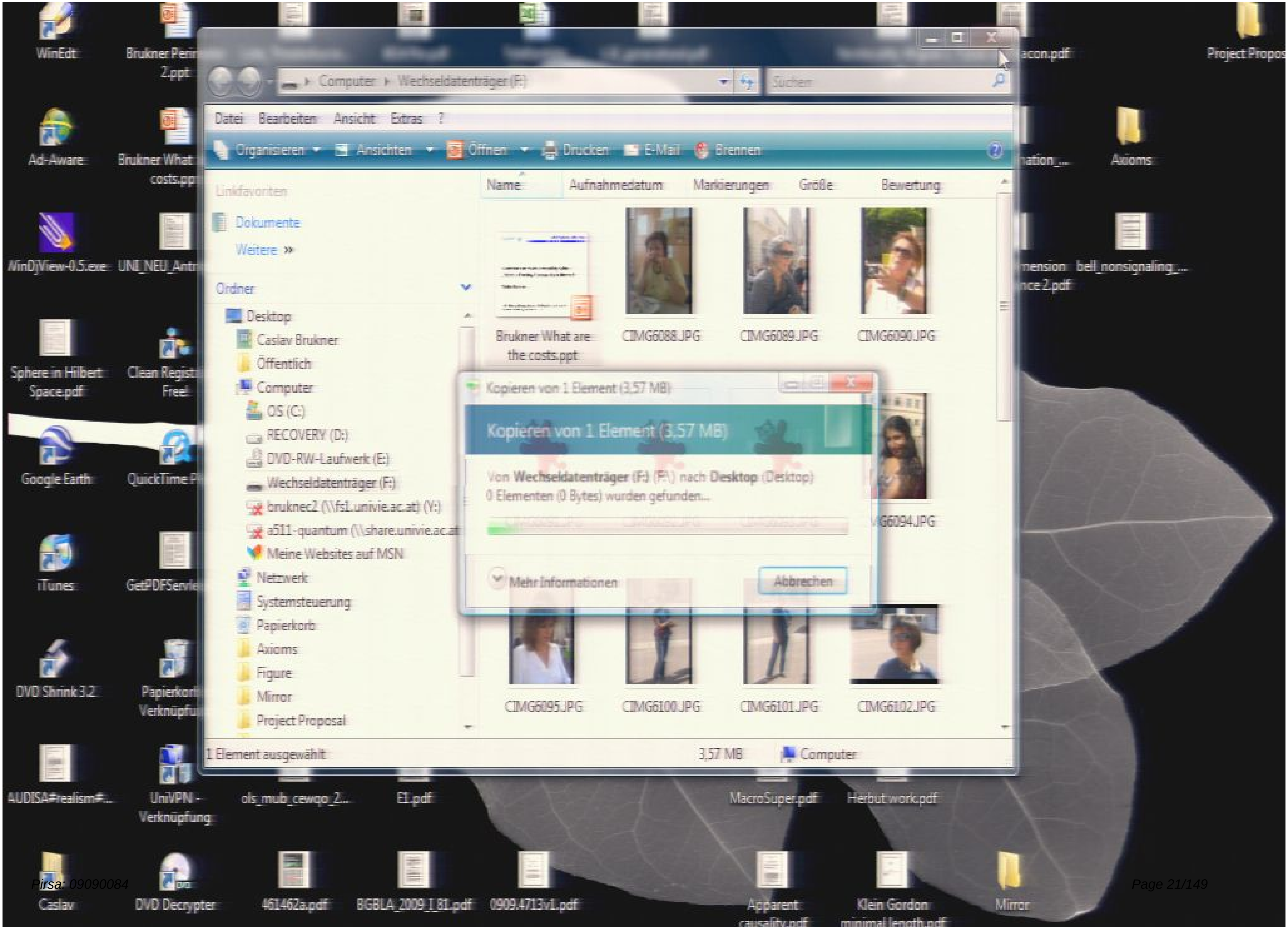

WinEdt
BruknerPerimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
rausendorf.pdf
detection profiles proof.pdf
finite_information_...
Axioms
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Abmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Figure
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE....
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
UniVPN - Verknüpfung
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror


WinEdt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
rausendorf.pdf
detection profiles proof.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Abmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Templeton Proram.eml
Figure
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE....
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
AUDISA#realism#...
UniVPN - Verknüpfung
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
Typ: Adobe Acrobat-Dokument
Größe: 1,31 MB
Änderungsdatum: 24.09.2009 14:14
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror

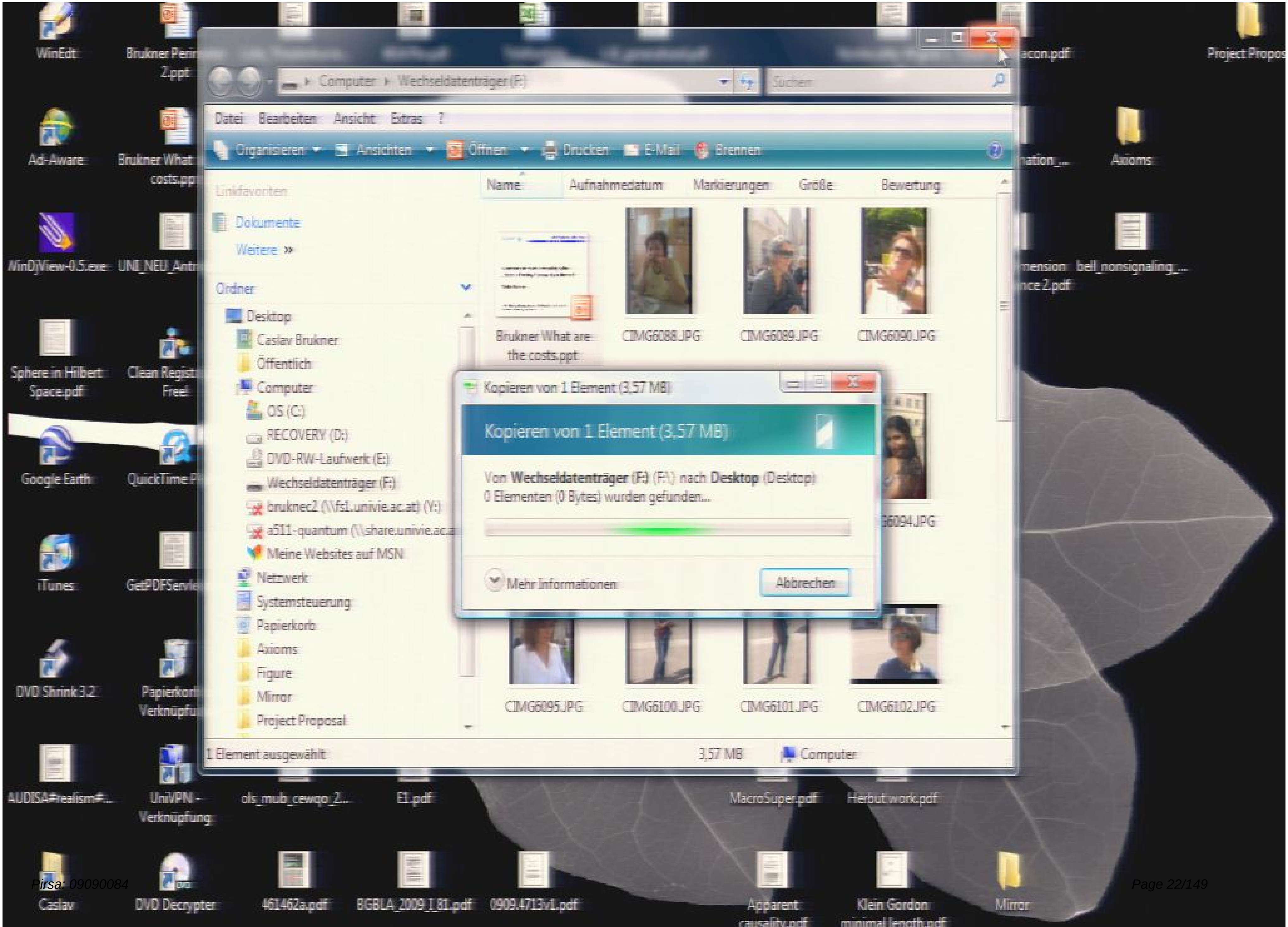

Automatische Wiedergabe
Wechseldatenträger (F:)
Immer für Bilder durchführen:
Bilder
Bilder importieren
mit Windows
Bilder anzeigen
mit Windows
Bilder anzeigen
mit Windows Media Center
Allgemeine Optionen
Ordner öffnen, um Dateien anzuzeigen
mit Windows-Explorer
Standard in der Systemsteuerung festlegen
WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
ReconstructionDB...
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE...
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
AUDISA#realism#...
UniVPN - Verknüpfung
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror

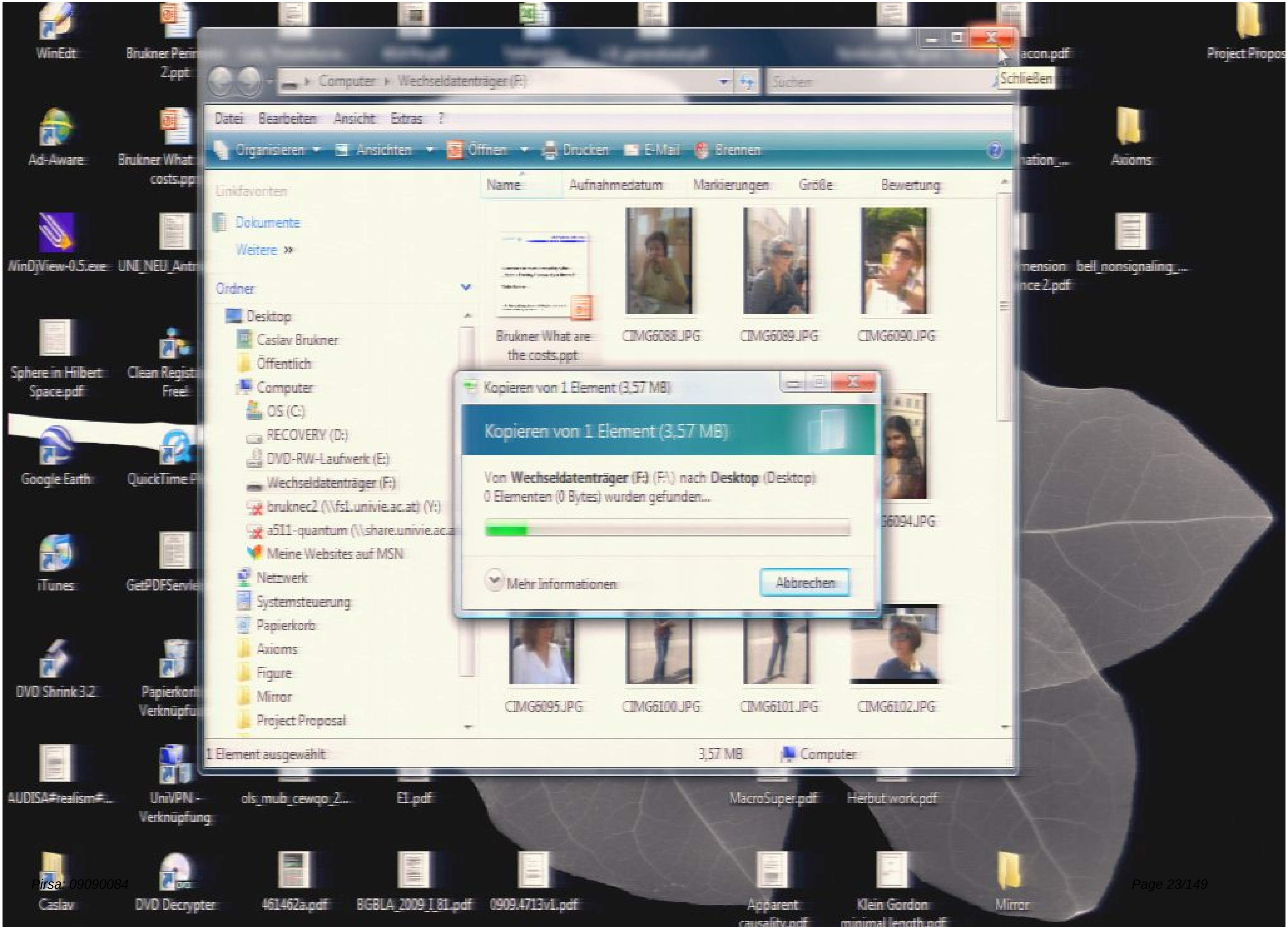

Automatische Wiedergabe
Wechseldatenträger (F:)
Immer für Bilder durchführen:
Bilder
Bilder importieren
mit Windows
Bilder anzeigen
mit Windows
Bilder anzeigen
mit Windows Media Center
Allgemeine Optionen
Ordner öffnen, um Dateien anzuzeigen
mit Windows-Explorer
Standard in der Systemsteuerung festlegen
WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner's .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Correlations of Cluster states.pdf
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE...
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
AUDISA#realism#...
UniVPN - Verknüpfung
ols_mub_cewqo_2...
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror

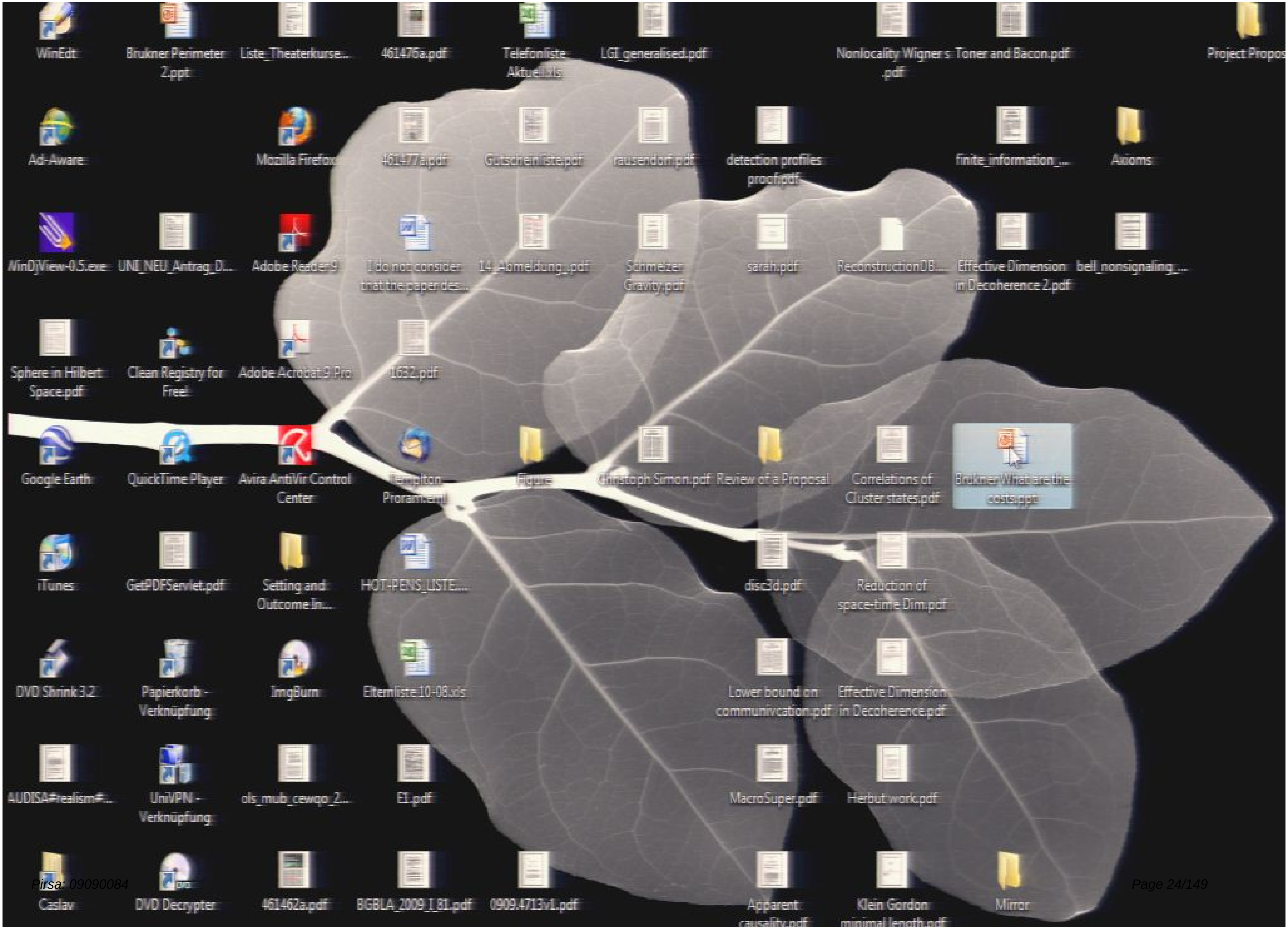

WinEdt
Ad-Aware
WinDjView-0.5.exe
Sphere in Hilbert Space.pdf
Google Earth
iTunes
DVD Shrink 3.2
AUDISA#realism#...
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror
UniVPN - Verknüpfung
ols_mub_cewqo_2...
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Project Propos
Axioms
bell_nonsignaling_...
Computer ▸ Wechseldatenträger (F:)
Suchen
Datei Bearbeiten Ansicht Extras ?
Organisieren Ansichten Diashow Brennen
Linkfavoriten
Dokumente
Weitere »
Ordner
Desktop
Caslav Brukner
Öffentlich
Computer
OS (C:)
RECOVERY (D:)
DVD-RW-Laufwerk (E:)
Wechseldatenträger (F:)
bruknec2 (\\fs1.univie.ac.at) (Y:)
a511-quantum (\\share.univie.ac.at
Meine Websites auf MSN
Netzwerk
Systemsteuerung
Papierkorb
Axioms
Figure
Mirror
Project Proposal
Name Aufnahmedatum Markierungen Größe Bewertung
Brukner What are the costs.ppt
CIMG6088.JPG
CIMG6089.JPG
CIMG6090.JPG
CIMG6091.JPG
CIMG6092.JPG
CIMG6093.JPG
CIMG6094.JPG
CIMG6095.JPG
CIMG6100.JPG
CIMG6101.JPG
CIMG6102.JPG
28 Elemente
Computer

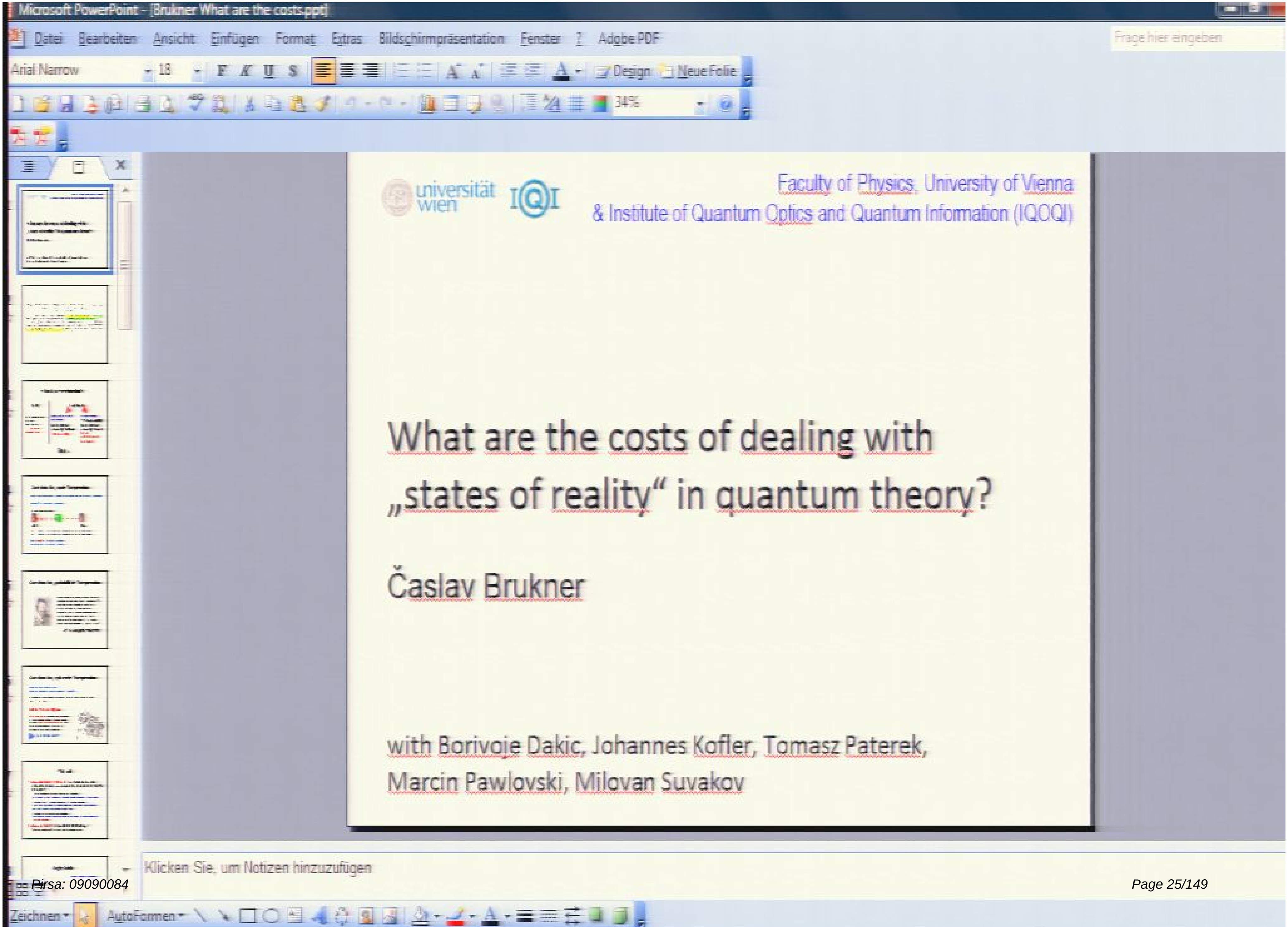


Computer ▸ Wechseldatenträger (F:)
Suchen
Datei Bearbeiten Ansicht Extras ?
Organisieren Ansichten Öffnen Drucken E-Mail Brennen
Linkfavoriten
Dokumente
Weitere »
Ordner
Desktop
Caslav Brukner
Öffentlich
Computer
OS (C:)
RECOVERY (D:)
DVD-RW-Laufwerk (E:)
Wechseldatenträger (F:)
bruknec2 (\\fs1.univie.ac.at) (Y:)
Meine Websites auf MSN
Netzwerk
Systemsteuerung
Papierkorb
Axioms
Figure
Mirror
Project Proposal
Name Aufnahmedatum Markierungen Größe Bewertung
Brukner What are the costs.ppt
CIMG6088.JPG
CIMG6089.JPG
CIMG6090.JPG
CIMG6094.JPG
CIMG6095.JPG
CIMG6100.JPG
CIMG6101.JPG
CIMG6102.JPG
Kopieren von 1 Element (3,57 MB)
Von Wechseldatenträger (F:) (F:\) nach Desktop (Desktop)
0 Elementen (0 Bytes) wurden gefunden...
Mehr Informationen
Abbrechen
1 Element ausgewählt
3,57 MB
Computer
WinEdt
Ad-Aware
WinDjView-0.5.exe
Sphere in Hilbert Space.pdf
Google Earth
iTunes
DVD Shrink 3.2
AUDISA#realism#...
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror
MacroSuper.pdf
Herbut work.pdf
E1.pdf
ols_mub_cewqo_2...
UniVPN - Verknüpfung
Project Propos
Axioms
bell_nonsignaling_...


Computer ▸ Wechseldatenträger (F:)
Suchen
Datei Bearbeiten Ansicht Extras ?
Organisieren Ansichten Öffnen Drucken E-Mail Brennen
Linkfavoriten
Dokumente
Weitere »
Ordner
Desktop
Caslav Brukner
Öffentlich
Computer
OS (C:)
RECOVERY (D:)
DVD-RW-Laufwerk (E:)
Wechseldatenträger (F:)
bruknec2 (\\fs1.univie.ac.at) (Y:)
a511-quantum (\\share.univie.ac.a
Meine Websites auf MSN
Netzwerk
Systemsteuerung
Papierkorb
Axioms
Figure
Mirror
Project Proposal
Name Aufnahmedatum Markierungen Größe Bewertung
Brukner What are the costs.ppt
CIMG6088.JPG
CIMG6089.JPG
CIMG6090.JPG
CIMG6095.JPG
CIMG6100.JPG
CIMG6101.JPG
CIMG6102.JPG
1 Element ausgewählt
3,57 MB
Computer
Kopieren von 1 Element (3,57 MB)
Von Wechseldatenträger (F:) (F:\) nach Desktop (Desktop)
0 Elementen (0 Bytes) wurden gefunden...
Mehr Informationen
Abbrechen
WinEdt
Ad-Aware
Sphere in Hilbert Space.pdf
Google Earth
iTunes
DVD Shrink 3.2
AUDISA#realism#...
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror
Project Propos
Axioms
bell_nonsignaling_...


Computer ▸ Wechseldatenträger (F:)
Suchen
Schließen
Datei Bearbeiten Ansicht Extras ?
Organisieren Ansichten Öffnen Drucken E-Mail Brennen
Linkfavoriten
Dokumente
Weitere »
Ordner
Desktop
Caslav Brukner
Öffentlich
Computer
OS (C:)
RECOVERY (D:)
DVD-RW-Laufwerk (E:)
Wechseldatenträger (F:)
Meine Websites auf MSN
Netzwerk
Systemsteuerung
Papierkorb
Axioms
Figure
Mirror
Project Proposal
Name Aufnahmedatum Markierungen Größe Bewertung
Brukner What are the costs.ppt
CIMG6088.JPG
CIMG6089.JPG
CIMG6090.JPG
CIMG6095.JPG
CIMG6100.JPG
CIMG6101.JPG
CIMG6102.JPG
Kopieren von 1 Element (3,57 MB)
Von Wechseldatenträger (F:) (F:\) nach Desktop (Desktop)
0 Elementen (0 Bytes) wurden gefunden...
Mehr Informationen
Abbrechen
1 Element ausgewählt 3,57 MB Computer
WinEdt
Ad-Aware
Sphere in Hilbert Space.pdf
Google Earth
iTunes
DVD Shrink 3.2
Caslav
DVD Decrypter
UniVPN - Verknüpfung
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Axioms
Mirror
Apparent causality.pdf
Klein Gordon minimal length.pdf
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf


WinEdt
Brukner Perimeter 2.ppt
Liste_Theaterkurse...
461476a.pdf
Telefonliste Aktuell.xls
LGI_generalised.pdf
Nonlocality Wigner s .pdf
Toner and Bacon.pdf
Ad-Aware
Mozilla Firefox
461477a.pdf
Gutscheinliste.pdf
rausendorf.pdf
detection profiles proof.pdf
finite_information_...
Axioms
WinDjView-0.5.exe
UNI_NEU_Antrag_D...
Adobe Reader 9
I do not consider that the paper des...
14_Abmeldung_.pdf
Schmelzer Gravity.pdf
sarah.pdf
ReconstructionDB....
Effective Dimension in Decoherence 2.pdf
bell_nonsignaling_...
Sphere in Hilbert Space.pdf
Clean Registry for Free!
Adobe Acrobat 9 Pro
1632.pdf
Google Earth
QuickTime Player
Avira AntiVir Control Center
Christoph Simon.pdf
Review of a Proposal
Correlations of Cluster states.pdf
Brukner What are the costs.ppt
iTunes
GetPDFServlet.pdf
Setting and Outcome In...
HOT-PENS_LISTE....
disc3d.pdf
Reduction of space-time Dim.pdf
DVD Shrink 3.2
Papierkorb - Verknüpfung
ImgBurn
Elternliste 10-08.xls
Lower bound on communivcation.pdf
Effective Dimension in Decoherence.pdf
UniVPN - Verknüpfung
ols_mub_cewqo_2...
E1.pdf
MacroSuper.pdf
Herbut work.pdf
Caslav
DVD Decrypter
461462a.pdf
BGBLA_2009_I_81.pdf
0909.4713v1.pdf
Apparent causality.pdf
Klein Gordon minimal length.pdf
Mirror


Microsoft PowerPoint - [Brukner What are the costs.ppt]
Datei Bearbeiten Ansicht Einfügen Format Extras Bildschirmpräsentation Fenster ? Adobe PDF
universität wien
IQOQI
Faculty of Physics, University of Vienna
& Institute of Quantum Optics and Quantum Information (IQOQI)
What are the costs of dealing with „states of reality“ in quantum theory?
Časlav Brukner
with Borivoje Dakic, Johannes Kofler, Tomasz Paterek, Marcin Pawlovski, Milovan Suvakov
Klicken Sie, um Notizen hinzuzufügen
Zeichnen AutoFormen

What is a wave function?

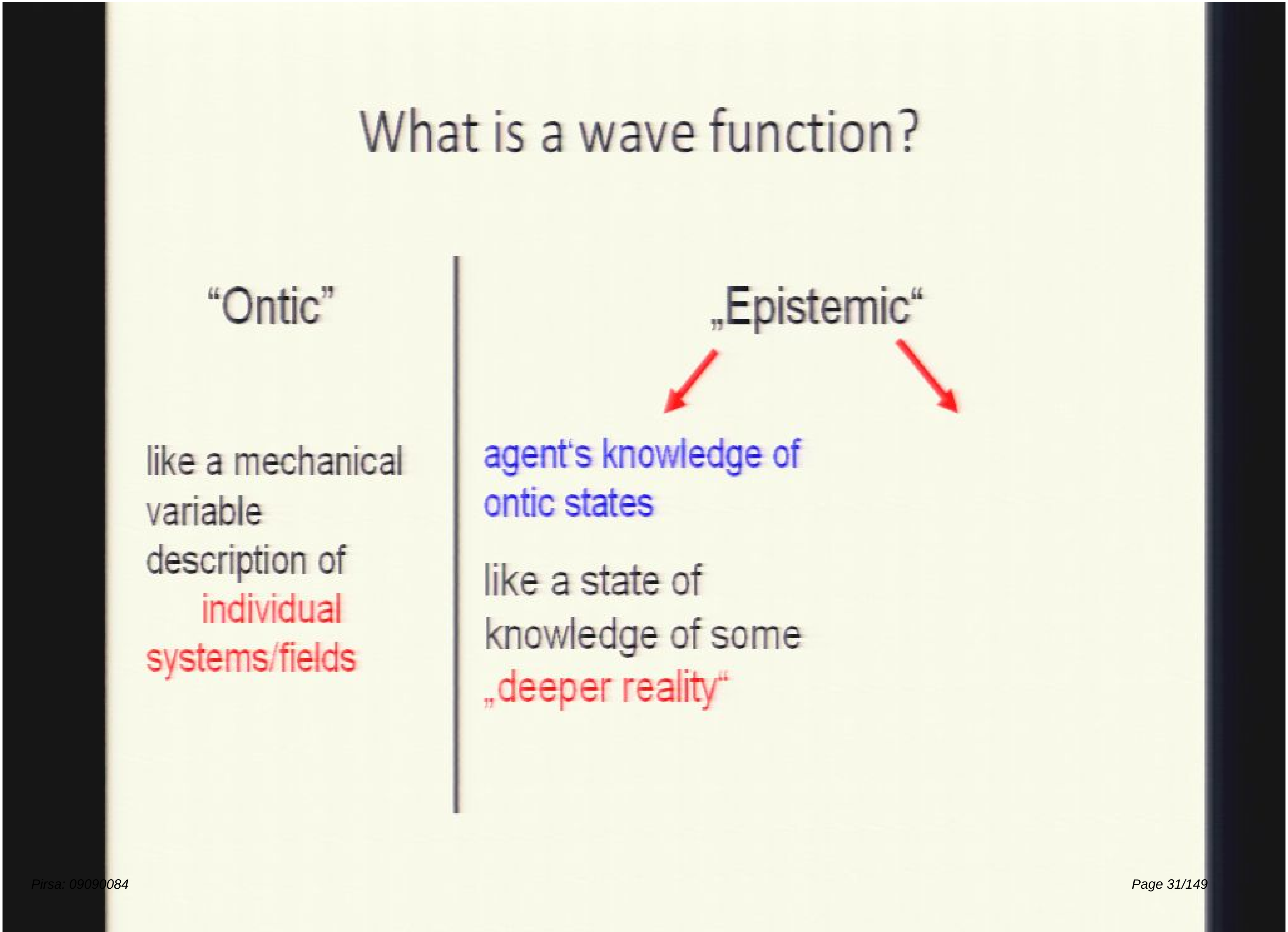
What is a wave function?

What is a wave function?

“Ontic”	„Epistemic“

What is a wave function?

"Ontic"	„Epistemic"
like a mechanical variable description of individual systems/fields	


What is a wave function?
“Ontic”
„Epistemic“
like a mechanical variable
description of individual systems/fields
agent‘s knowledge of ontic states
like a state of knowledge of some „deeper reality“

What is a wave function?

"Ontic"

like a mechanical variable description of individual systems/fields

„Epistemic"

agent's knowledge of ontic states

like a state of knowledge of some „deeper reality"

no ontic states

like a state of knowledge about future measurement outcomes

What is a wave function?

“Ontic”

like a mechanical variable description of individual systems/fields

„Epistemic“

agent‘s knowledge of ontic states

like a state of knowledge of some „deeper reality“

no ontic states =„Probabilistic“

like a state of knowledge about future measurement outcomes

What is a wave function?

"Ontic"	„Epistemic"	
like a mechanical variable description of individual systems/fields	agent's knowledge of ontic states	no ontic states =„Probabilistic"
	like a state of knowledge of some „deeper reality"	like a state of knowledge about future measurement outcomes

But ...

Questions for „ontic“ intepretation

Questions for „ontic“ intepretation

- What is the meaning of complex multidimensional wave function?

Questions for „ontic“ intepretation

- What is the meaning of complex multidimensional wave function?
- „Collaps“ of the wave function

Questions for „ontic" intepretation

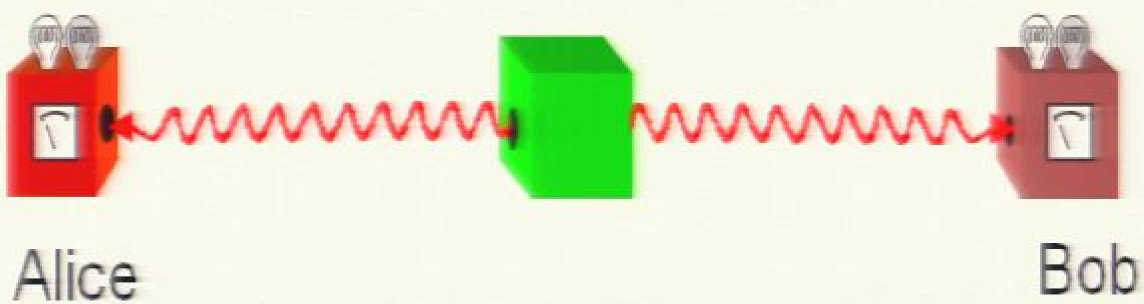
- What is the meaning of complex multidimensional wave function?
- „Collaps" of the wave function

... In Bell's test situation:

Questions for „ontic“ intepretation

- What is the meaning of complex multidimensional wave function?
- „Collaps“ of the wave function

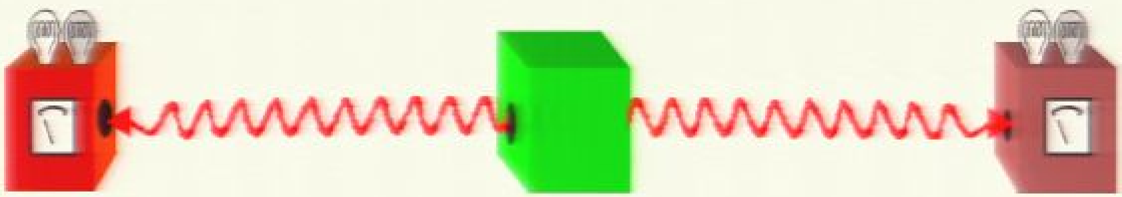
... In Bell‘s test situation:



Questions for „ontic“ intepretation

- What is the meaning of complex multidimensional wave function?
- „Collaps“ of the wave function

... In Bell‘s test situation:



Alice

Bob

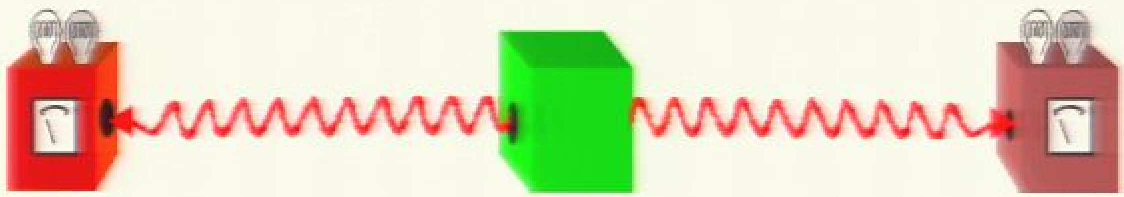
Ref. Frame 1: A‘s choice of setting before B‘s outcome
Ref. Frame 2: B‘s choice of setting before A‘s outcome

Questions for „ontic“ intepretation

- What is the meaning of complex multidimensional wave function?

- „Collaps“ of the wave function

... In Bell‘s test situation:



Alice

Bob

Ref. Frame 1: A‘s choice of setting before B‘s outcome
Ref. Frame 2: B‘s choice of setting before A‘s outcome

- Who „really“ influenced whom?
- And in which reference frame?

Questions for „probabilistic“ interpretation

Questions for „probabilistic" interpretation

Questions for „probabilistic“ interpretation

„What exactly qualifies some physical systems to play the role of „measurer“? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system ... with a PhD?“

John. S. Bell, Against "Measurement"

Questions for „epistemic“ interpretation

Questions for „epistemic" interpretation

What is distributed here?
What are states of some „deeper reality"?

Questions for „epistemic“ interpretation

What is distributed here?
What are states of some „deeper reality“?

Quantum probabilities in terms of lack of knowledge of the **real properties**

Questions for „epistemic“ interpretation

What is distributed here?
What are states of some „deeper reality“?

Quantum probabilities in terms of lack of knowledge of the **real properties**

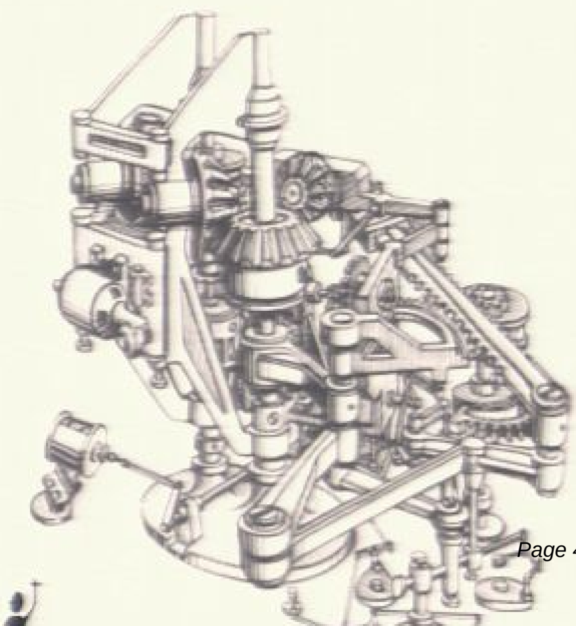
Hidden Variable Program

Questions for „epistemic“ interpretation

What is distributed here?
What are states of some „deeper reality“?

Quantum probabilities in terms of lack of knowledge of the **real properties**

Hidden Variable Program



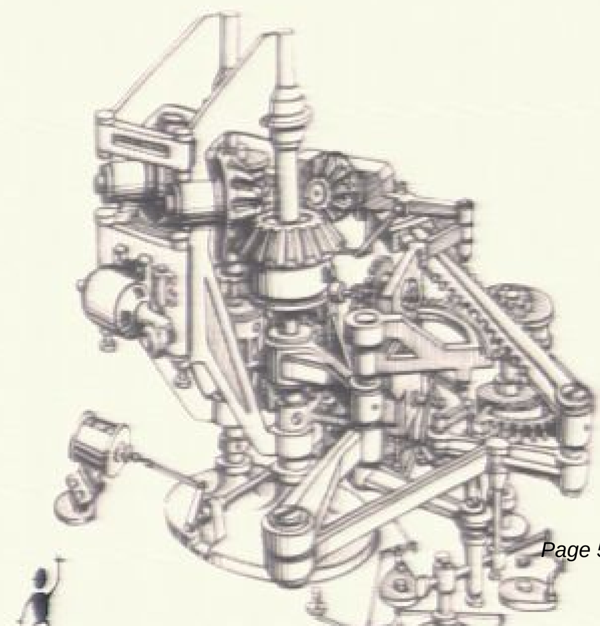
Questions for „epistemic“ interpretation

What is distributed here?
What are states of some „deeper reality“?

Quantum probabilities in terms of lack of knowledge of the **real properties**

Hidden Variable Program

Bell‘s theorem (respecting independence of experimenter‘s choice from the hidden variable): local realism excluded, but which (if not both) principles is violated is an open question



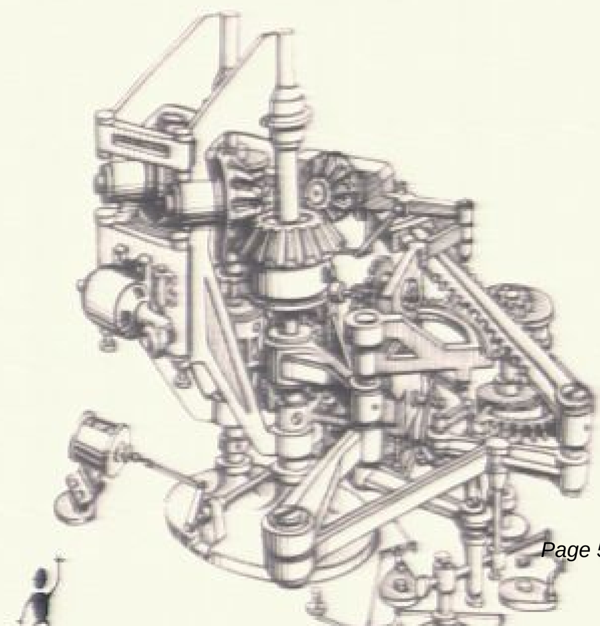
Questions for „epistemic“ interpretation

What is distributed here?
What are states of some „deeper reality“?

Quantum probabilities in terms of lack of knowledge of the **real properties**

Hidden Variable Program

Bell's theorem (respecting independence of experimenter's choice from the hidden variable): local realism excluded, but which (if not both) principles is violated is an open question



→ End of the road?

This talk

This talk

1. How plausible is "realism" in terms of the amount of resources, i.e. the number of hidden-variable states (HV), it requires?

This talk

1. How plausible is "realism" in terms of the amount of resources, i.e. the number of hidden-variable states (HV), it requires?

   L. Hardy (Stud.Hist.Philos.Mod.Phys. **35**, 267 (2004)):
   Infinite number of HVs required for all measurements already for a single qubit.

This talk

1. How plausible is "realism" in terms of the amount of resources, i.e. the number of hidden-variable states (HV), it requires?

   L. Hardy (Stud.Hist.Philos.Mod.Phys. **35**, 267 (2004)):
   Infinite number of HVs required for all measurements already for a single qubit.

   A. Montina (PRA 77, 022104 (2008), PRL 97, 180401 (2006)):
   In the limit of large number of measurements no realistic theory can describe nature more efficiently than quantum theory itself.

This talk

1. How plausible is "realism" in terms of the amount of resources, i.e. the number of hidden-variable states (HV), it requires?

   L. Hardy (Stud.Hist.Philos.Mod.Phys. **35**, 267 (2004)):
   Infinite number of HVs required for all measurements already for a single qubit.

   A. Montina (PRA 77, 022104 (2008), PRL 97, 180401 (2006)):
   In the limit of large number of measurements no realistic theory can describe nature more efficiently than quantum theory itself.

   T. Rudolph & N. Harigan (arXiv:0709.1149):
   Hoes does the number Ω(N) of HV scale with the number of measurements N?
   Less than Exp(N)?

This talk

1. How plausible is "realism" in terms of the amount of resources, i.e. the number of hidden-variable states (HV), it requires?

   L. Hardy (Stud.Hist.Philos.Mod.Phys. **35**, 267 (2004)):
   Infinite number of HVs required for all measurements already for a single qubit.

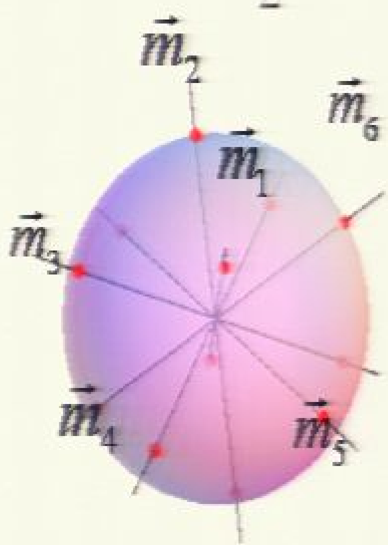
   A. Montina (PRA 77, 022104 (2008), PRL 97, 180401 (2006)):
   In the limit of large number of measurements no realistic theory can describe nature more efficiently than quantum theory itself.

   T. Rudolph & N. Harigan (arXiv:0709.1149):
   Hoes does the number $\Omega(N)$ of HV scale with the number of measurements N?
   Less than Exp(N)?

2. How "non-local" is a non-local realistic theory?
   "Bell's Non-locality" ≠ Superluminal signalling?

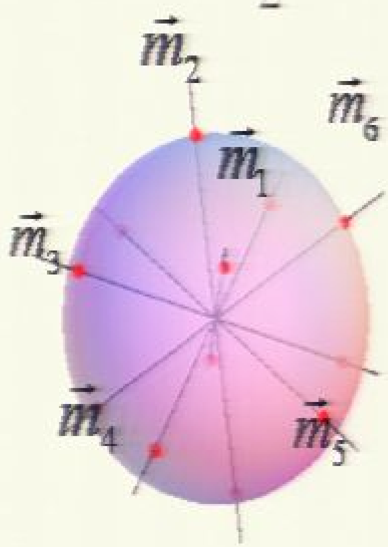
Single Qubit

$\vec{x} \in S^2, \quad p_i = \frac{1}{2}(1 + \vec{x}\vec{m}_i)$



Single Qubit

$\vec{x} \in S^2, \quad p_i = \frac{1}{2}(1 + \vec{x}\vec{m}_i)$



Measurement directions

$\vec{m}_1 \; \vec{m}_2 \; \vec{m}_3 \; ... \; \vec{m}_N$

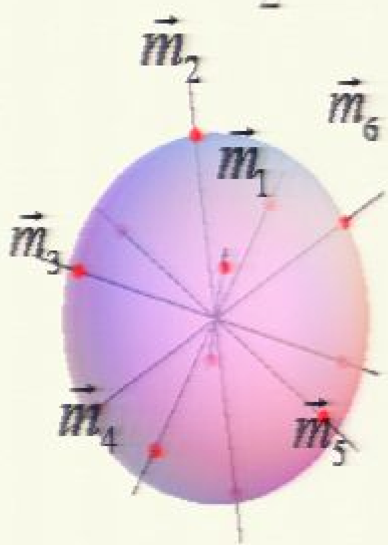
$$\vec{p} = \begin{pmatrix} p_1 & p_2 & p_3 & ... & p_N \end{pmatrix}^T$$

$$\vec{O}_{101...1} = \begin{pmatrix} 1 & 0 & 1 & ... & 1 \end{pmatrix}^T$$

$\Omega = 2^N$ Hidden-Variable (HV) States

Single Qubit

$\vec{x} \in S^2, \quad p_i = \frac{1}{2}(1 + \vec{x}\vec{m}_i)$



Measurement directions

$\vec{m}_1 \; \vec{m}_2 \; \vec{m}_3 \; ... \; \vec{m}_N$

$$\vec{p} = \begin{pmatrix} p_1 & p_2 & p_3 & ... & p_N \end{pmatrix}^T$$

$$\vec{O}_{101...1} = \begin{pmatrix} 1 & 0 & 1 & ... & 1 \end{pmatrix}^T$$

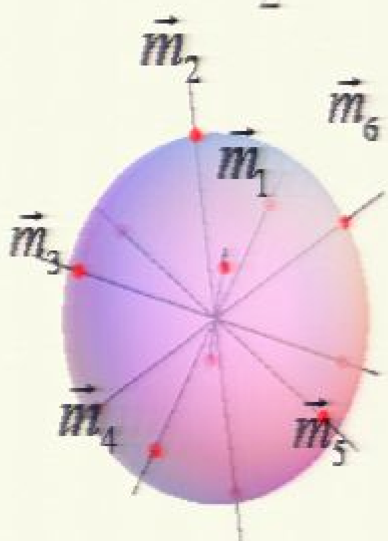
$\Omega = 2^N$ Hidden-Variable (HV) States

Any quantum state is a mixture over HVs:

$$\forall \vec{x} \in S^2, \quad \vec{p}(\vec{x}) = \sum_{i=1}^{\Omega} \alpha_i \vec{O}_i$$

Single Qubit

$\vec{x} \in S^2, \quad p_i = \frac{1}{2}(1 + \vec{x}\vec{m}_i)$



Measurement directions

$$\vec{m}_1 \; \vec{m}_2 \; \vec{m}_3 \; \dots \; \vec{m}_N$$

$$\downarrow \; \downarrow \; \downarrow \; \quad \downarrow$$

$$\vec{p} = \begin{pmatrix} p_1 & p_2 & p_3 & \dots & p_N \end{pmatrix}^T$$

$$\vec{O}_{101\dots1} = \begin{pmatrix} 1 & 0 & 1 & \dots & 1 \end{pmatrix}^T$$

$\Omega = 2^N$ Hidden-Variable (HV) States

Any quantum state is a mixture over HVs: $\forall \vec{x} \in S^2, \quad \vec{p}(\vec{x}) = \sum_{i=1}^{\Omega} \alpha_i \vec{O}_i$

What is the minimal number Ω_{min} of HVs for all quantum states (*preparation-universal*) for a given set of *N* measurements?

$$\Omega_{min} = ?$$

Caratheodory´s theorem

A point in a convex polytope in $\mathbf{R}^N$ can be written as a convex combination of N+1 vertices

Caratheodory´s theorem

A point in a convex polytope in $\mathbf{R}^N$ can be written as a convex combination of *N*+1 vertices

$$\begin{matrix} \vec{m}_1 & & \vec{m}_2 & & \vec{m}_3 & & \dots & & \vec{m}_N \\ \blacktriangledown & & \blacktriangledown & & \blacktriangledown & & & & \blacktriangledown \\ p_1 & \leq & p_2 & \leq & p_3 & & \dots & \leq & p_N \end{matrix}$$

0	0	0	....	0	$1-p_N$
1	1	1	....	1	p_1
0	1	1	....	1	p_2-p_1
0	0	1	....	1	p_3-p_2
⋮	⋮	⋮	⋮	⋮	
0	0	0	....	1	p_N-p_{N-1}

Caratheodory´s theorem

A point in a convex polytope in $\mathbf{R}^N$ can be written as a convex combination of N+1 vertices

$$\begin{array}{ccccccccc} \vec{m}_1 & & \vec{m}_2 & & \vec{m}_3 & & \dots & & \vec{m}_N \\ \downarrow & & \downarrow & & \downarrow & & & & \downarrow \\ p_1 & \leq & p_2 & \leq & p_3 & & \dots & \leq & p_N \end{array}$$

← Measurement Directions

0	0	0	....	0	$1-p_N$
1	1	1	....	1	p_1
0	1	1	....	1	p_2-p_1
0	0	1	....	1	p_3-p_2
⋮	⋮	⋮	⋮	⋮	
0	0	0	....	1	p_N-p_{N-1}

Caratheodory´s theorem

A point in a convex polytope in $\mathbf{R}^N$ can be written as a convex combination of N+1 vertices

$$\vec{m}_1 \quad \vec{m}_2 \quad \vec{m}_3 \quad \dots \quad \vec{m}_N \quad \leftarrow \text{Measurement Directions}$$

$$\downarrow \quad \downarrow \quad \downarrow \quad \quad \downarrow$$

$$p_1 \leq p_2 \leq p_3 \ \dots \leq p_N \quad \leftarrow \text{Quantum Probabilities}$$

0	0	0	....	0	$1-p_N$
1	1	1	....	1	p_1
0	1	1	....	1	p_2-p_1
0	0	1	....	1	p_3-p_2
⋮	⋮	⋮	⋮	⋮	
0	0	0	....	1	p_N-p_{N-1}

← Probabilities for N+1 HVs

Caratheodory´s theorem

A point in a convex polytope in $\mathbf{R}^N$ can be written as a convex combination of N+1 vertices

$$\vec{m}_1 \quad \vec{m}_2 \quad \vec{m}_3 \quad \ldots \quad \vec{m}_N$$

← Measurement Directions

$$p_1 \le p_2 \le p_3 \ \ldots \ \le p_N$$

← Quantum Probabilities

0	0	0	....	0	$1-p_N$
1	1	1	....	1	p_1
0	1	1	....	1	p_2-p_1
0	0	1	....	1	p_3-p_2
⋮	⋮	⋮	⋮	⋮	
0	0	0	....	1	p_N-p_{N-1}

← Probabilities for N+1 HVs

Spekkens' toy model

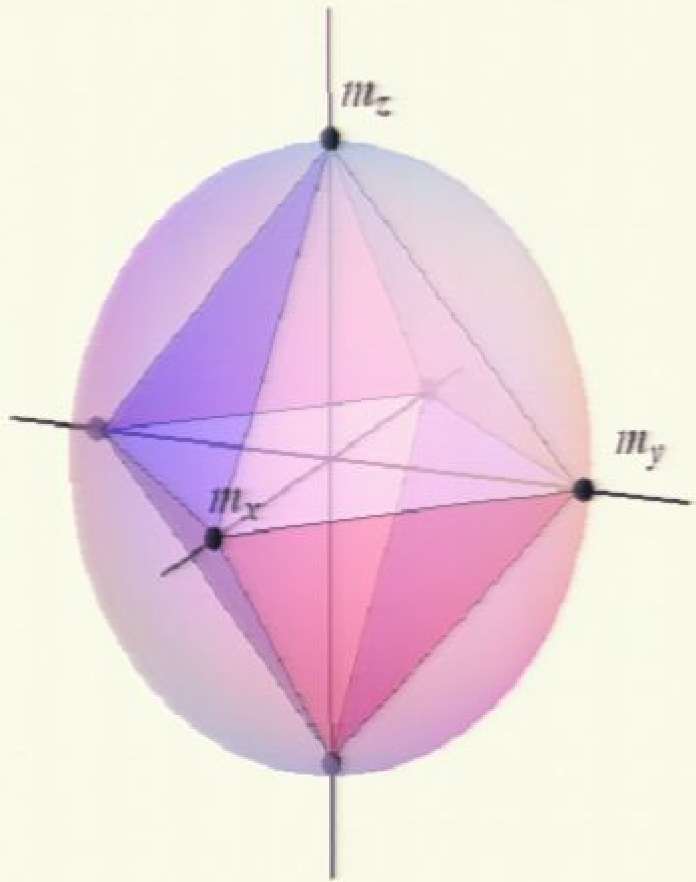
(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

- N=3 complementary measurements (*x*,*y*,*z*)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$

Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

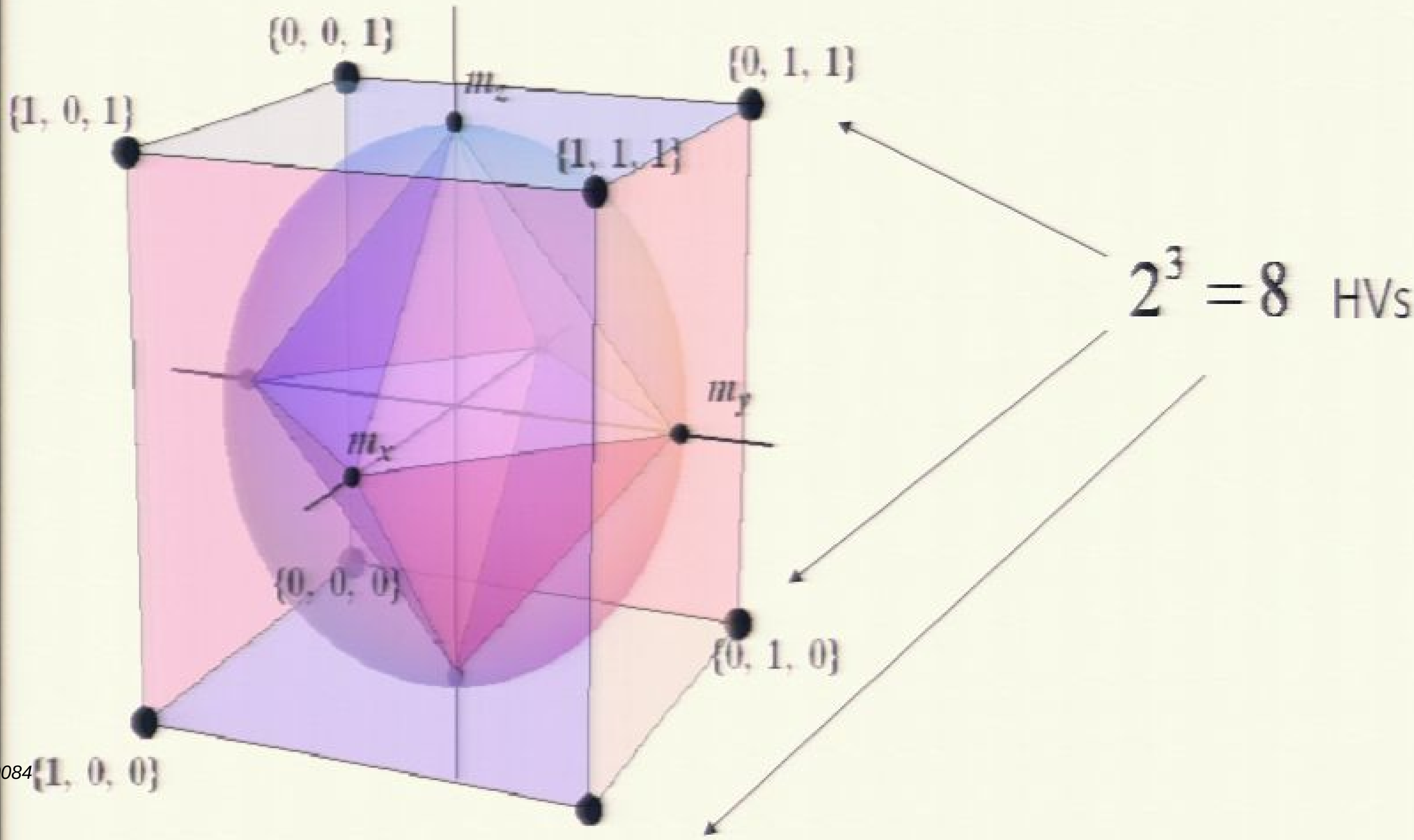
- N=3 complementary measurements (*x*,*y*,*z*)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$



Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

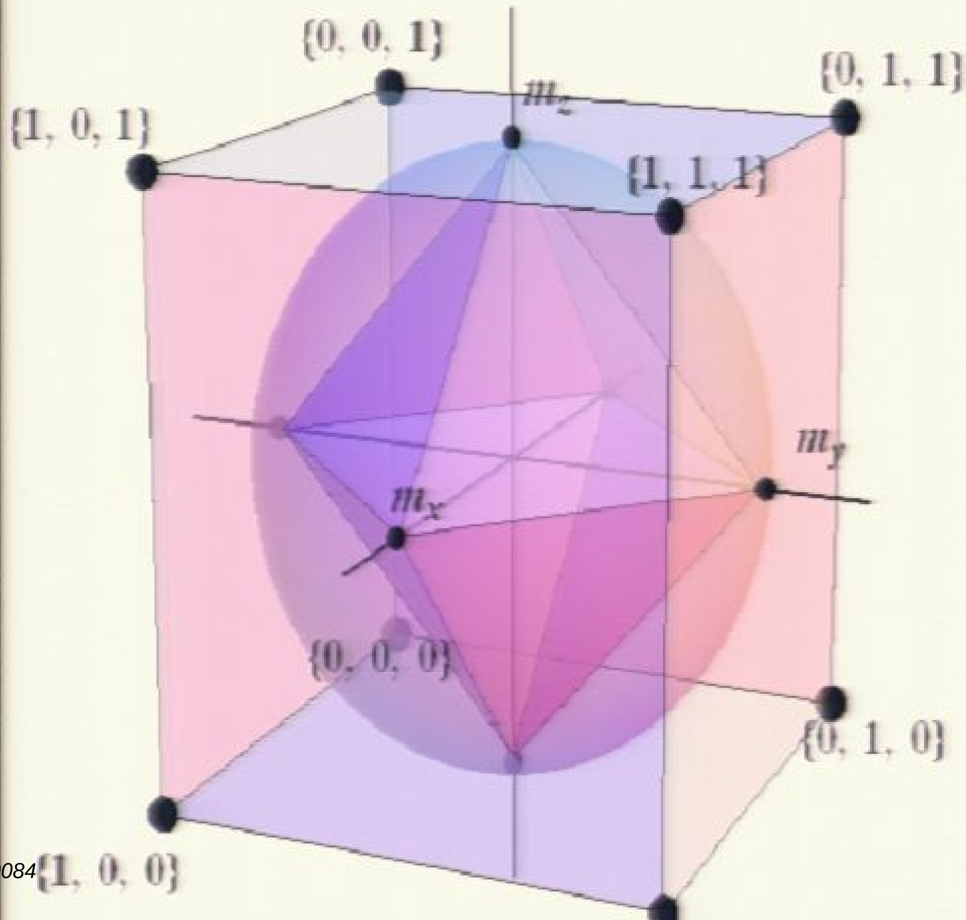
- N=3 complementary measurements (x,y,z)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$



Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

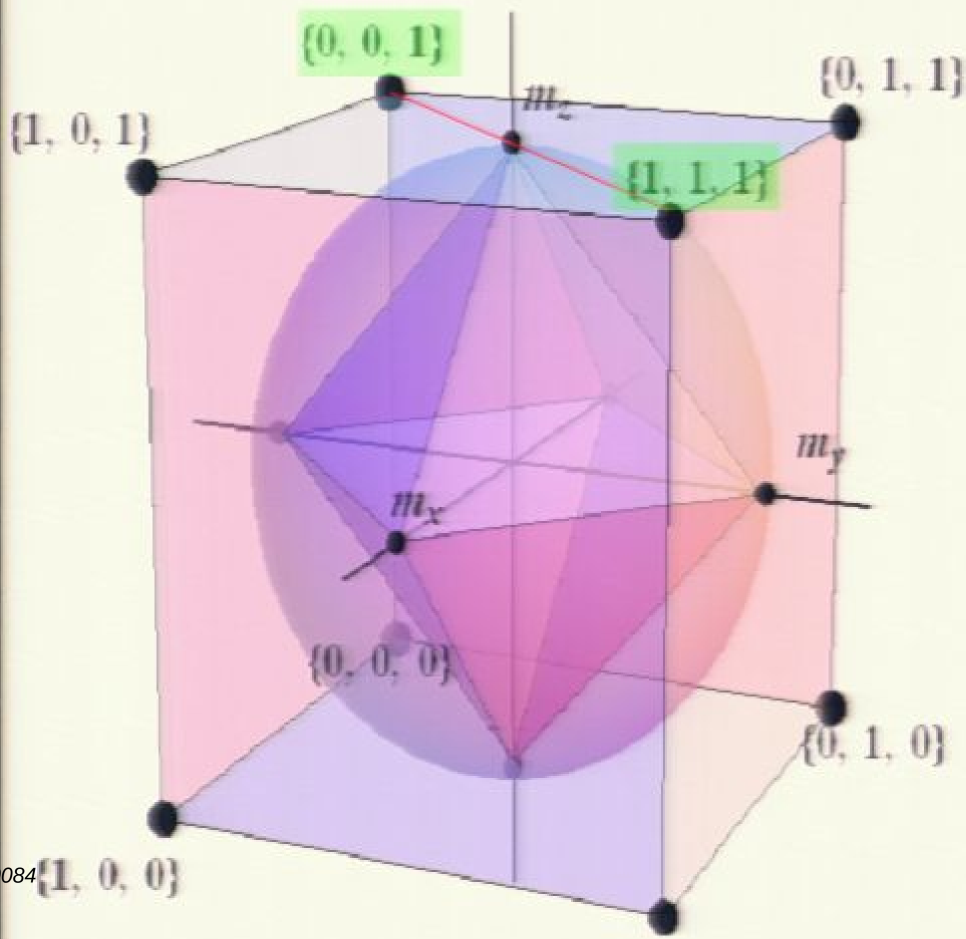
- N=3 complementary measurements (*x*,*y*,*z*)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$



Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

- N=3 complementary measurements (x,y,z)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$



$\vec{p}(\vec{m}_z)$ as 50-50% mixture

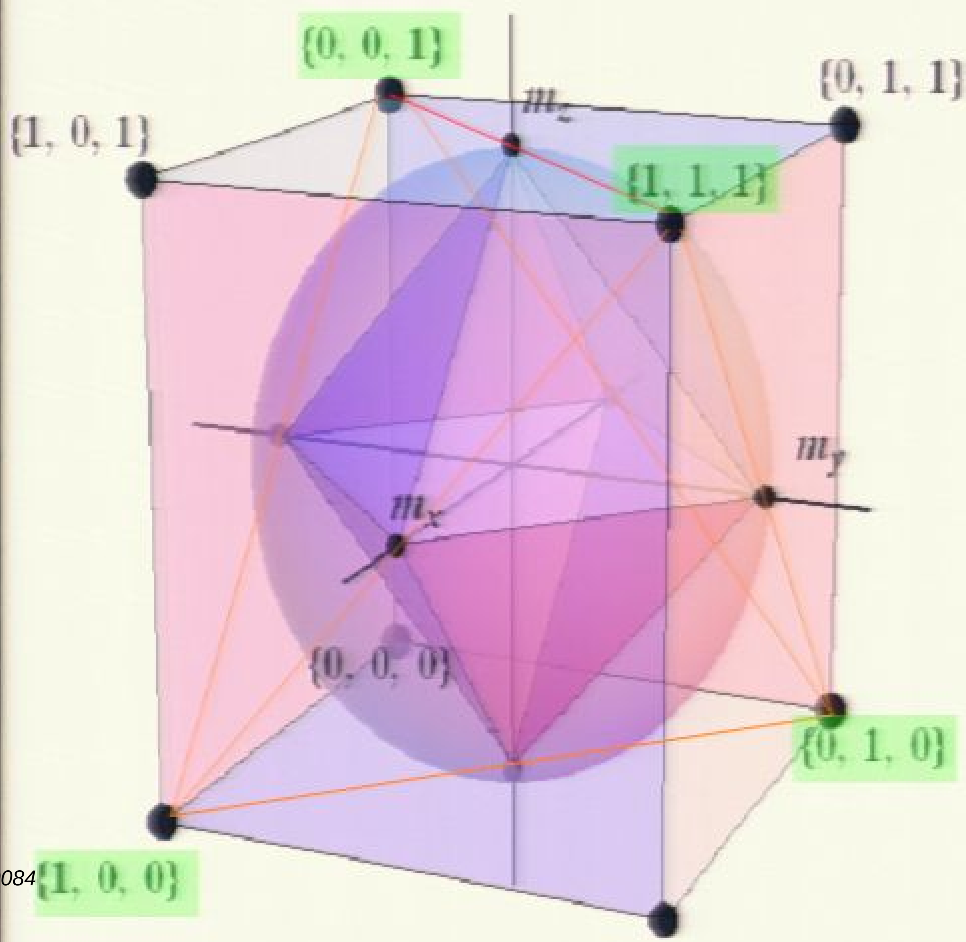
$$\vec{p}(\vec{m}_z) \equiv (p_x(\vec{m}_z), p_y(\vec{m}_z) p_z(\vec{m}_z))$$

$$= (\frac{1}{2}, \frac{1}{2}, 1) = \frac{1}{2}(0,0,1) + \frac{1}{2}(1,1,1)$$

Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

- N=3 complementary measurements (x,y,z)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$



$\vec{p}(\vec{m}_z)$ as 50-50% mixture

4 HVs needed

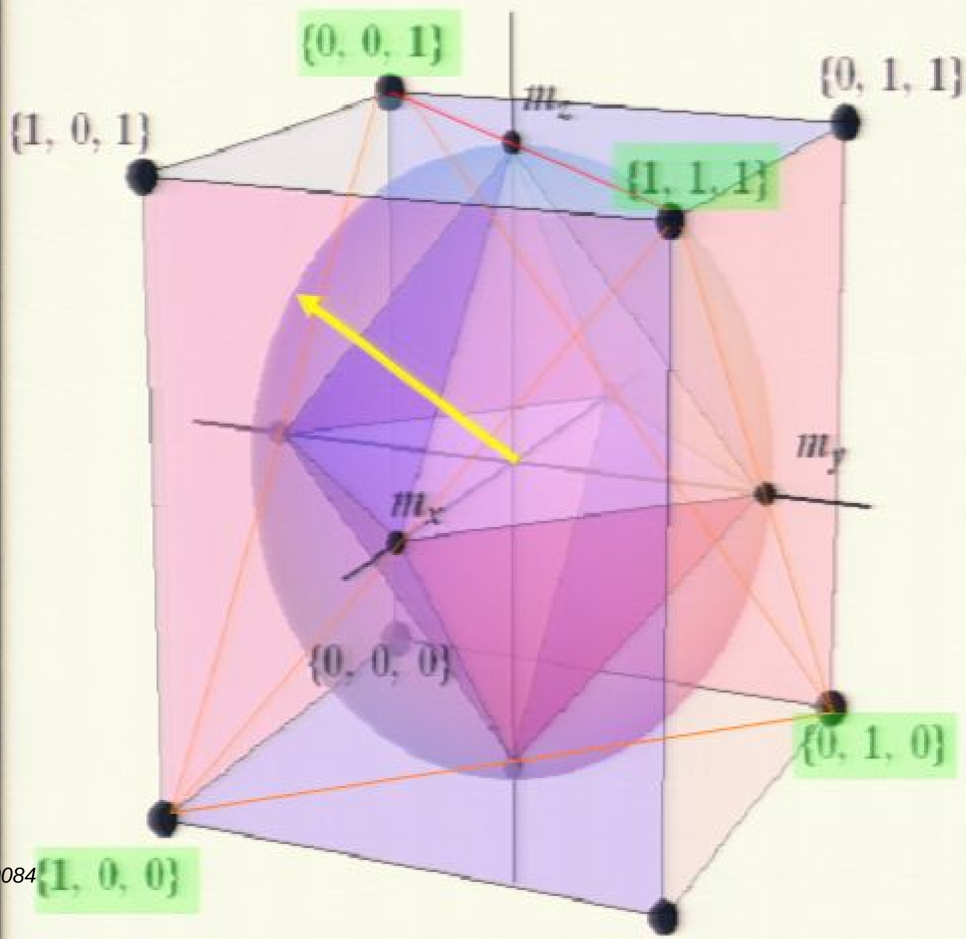
$$\vec{p}(\vec{m}_z) \equiv (p_x(\vec{m}_z), p_y(\vec{m}_z) p_z(\vec{m}_z))$$

$$= (\frac{1}{2}, \frac{1}{2}, 1) = \frac{1}{2}(0,0,1) + \frac{1}{2}(1,1,1)$$

Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

- N=3 complementary measurements (x,y,z)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$

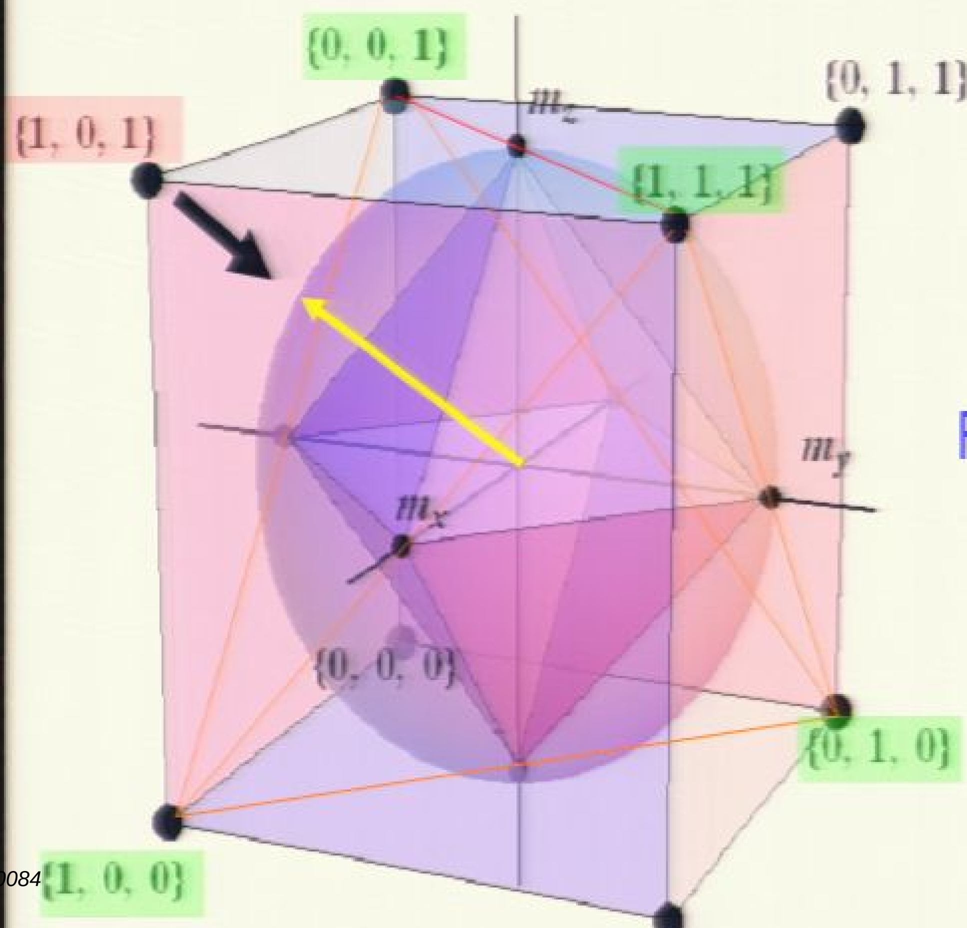


Outside tetrahedron?

Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

- N=3 complementary measurements (*x*,*y*,*z*)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$



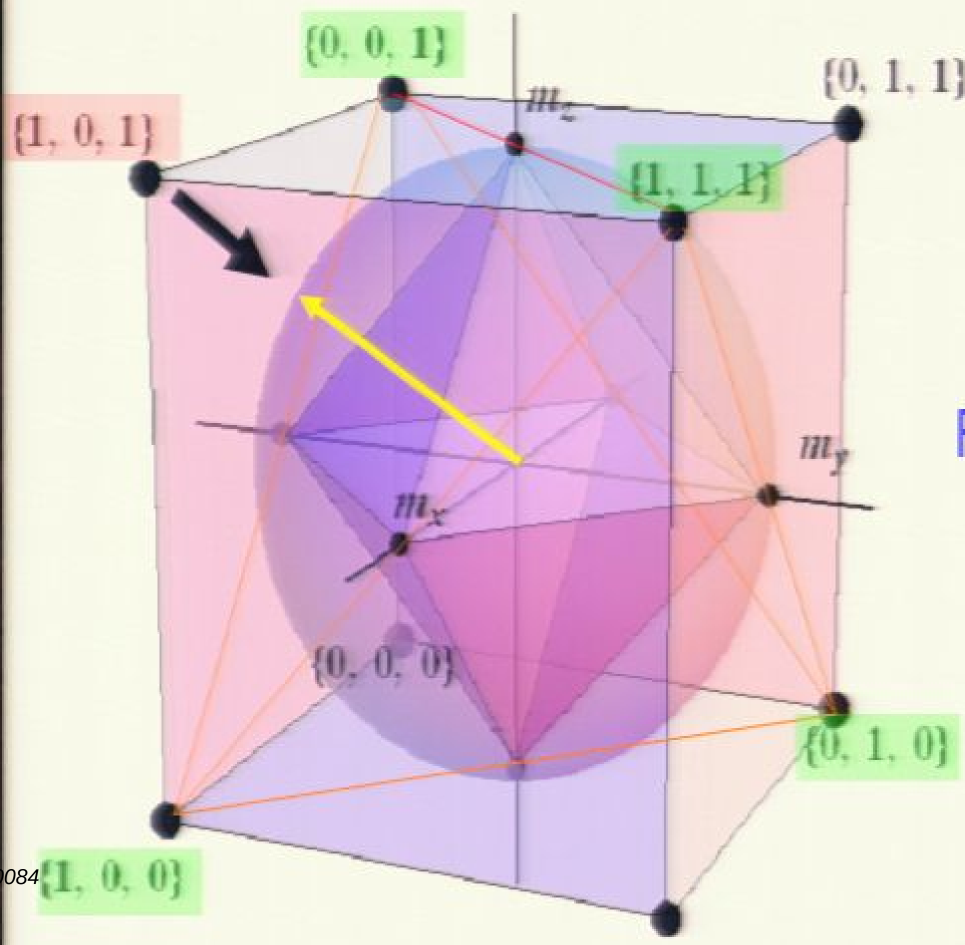
Outside tetrahedron?

For states outside of tetrahedron
All 2^3=8 HVs are needed!

Spekkens' toy model

(R. W. Spekkens, Phys. Rev. A, **75** 0323110 (2007))

- N=3 complementary measurements (*x*,*y*,*z*)
- HV model for 6 quantum states: $\{\pm\vec{m}_x, \pm\vec{m}_y, \pm\vec{m}_z\}$

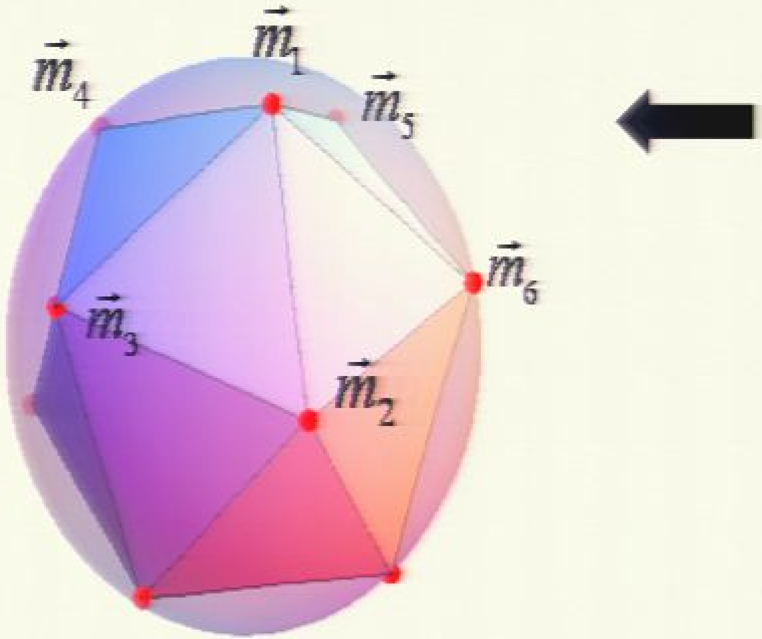


Outside tetrahedron?

For states outside of tetrahedron
All 2^3=8 HVs are needed!

HV-Model Based on Dual Polytope

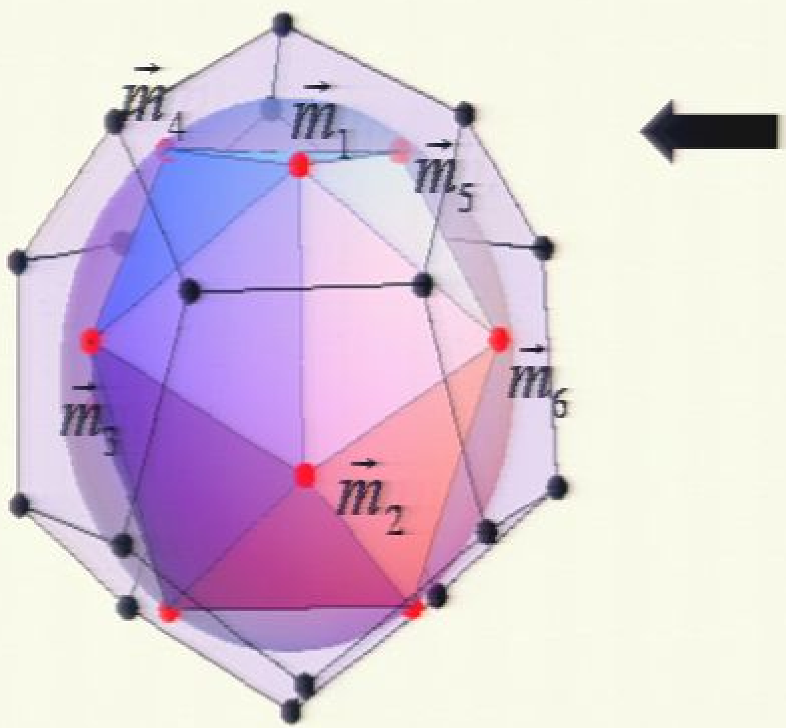
HV-Model Based on Dual Polytope



Measurement polytope

HV-Model Based on Dual Polytope

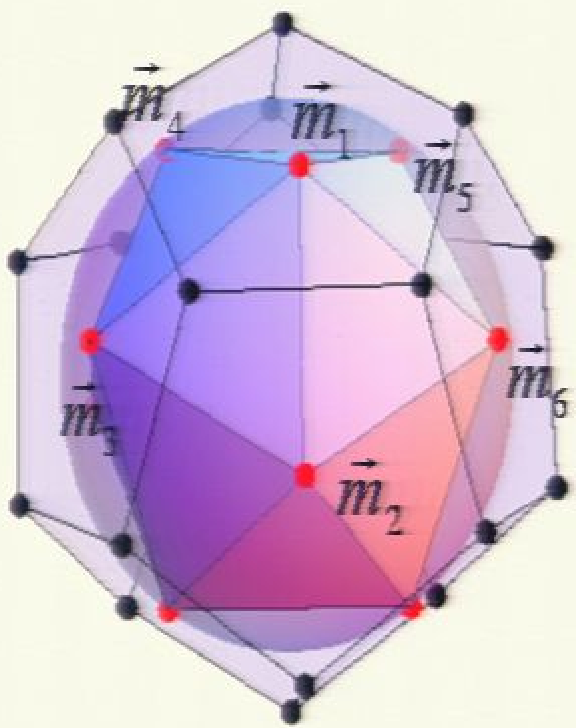
Dual Polytope: $\mathcal{P}_{(N)} = \{\mathbf{y} \in \mathbb{R}^3 \mid -1 \leq \mathbf{m}_n \mathbf{y} \leq 1, n = 1 \ldots N\}$



Dual polytope

HV-Model Based on Dual Polytope

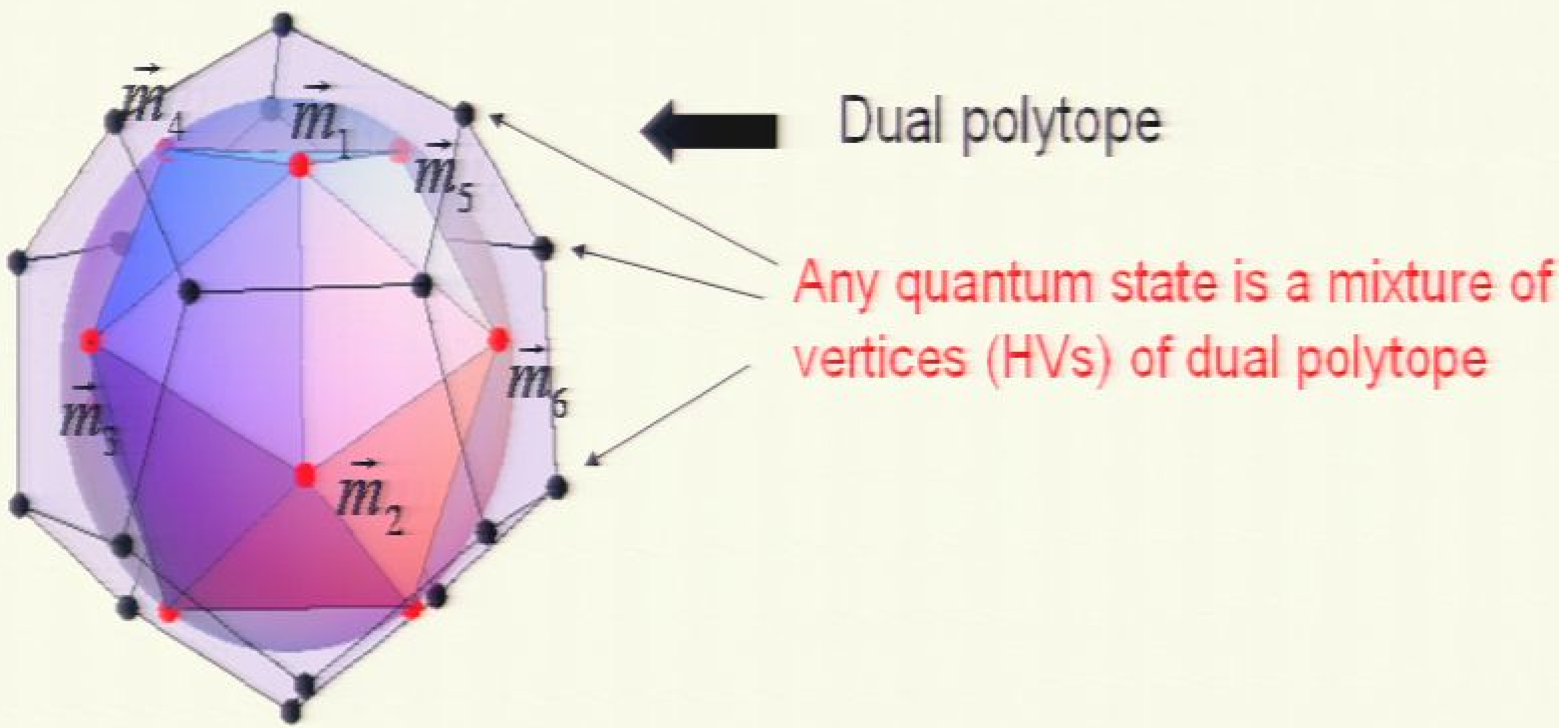
Dual Polytope: $\mathcal{D}_{\mathcal{M}} = \{\mathbf{y} \in \mathbb{R}^3 | -1 \leq \mathbf{m}_n \mathbf{y} \leq 1, n = 1 \ldots N\}$



Dual polytope

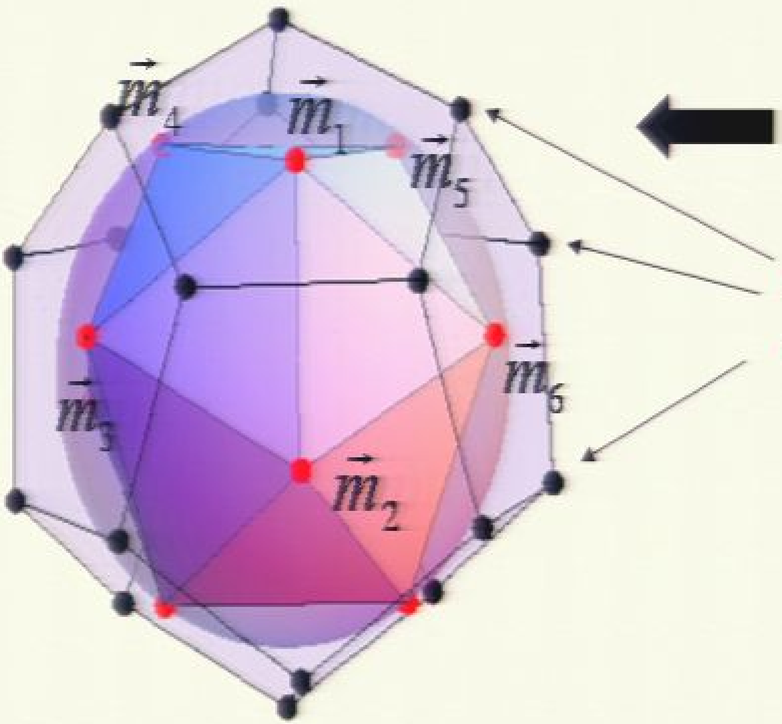
HV-Model Based on Dual Polytope

Dual Polytope: $\mathcal{D}_{\mathcal{M}} = \{\mathbf{y} \in \mathbb{R}^3 | -1 \leq \mathbf{m}_n \mathbf{y} \leq 1, n = 1 \ldots N\}$



HV-Model Based on Dual Polytope

Dual Polytope: $\mathcal{D}_{\mathcal{M}} = \{\mathbf{y} \in \mathbb{R}^3 | -1 \leq \mathbf{m}_n \mathbf{y} \leq 1, n = 1 \ldots N\}$



Dual polytope

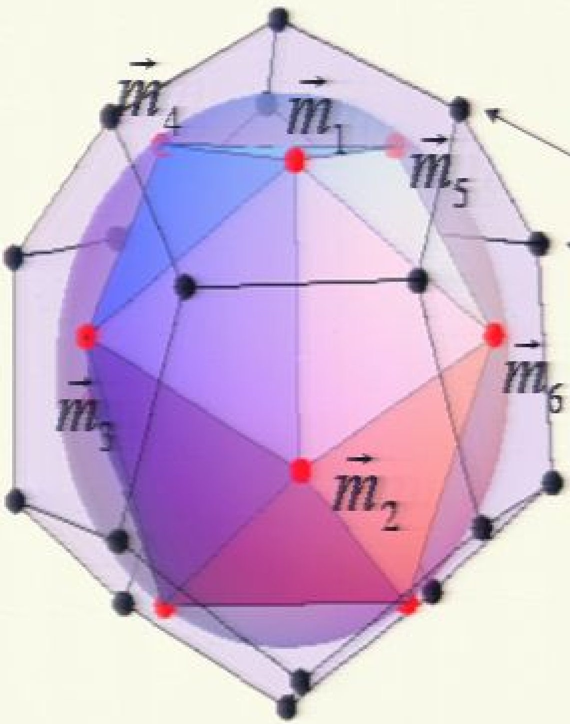
Any quantum state is a mixture of vertices (HVs) of dual polytope

$$\vec{x} = \sum_i \alpha_i(\vec{x}) \vec{O}_i$$

$\vec{O}_i$ can be **longer** than quantum Bloch vectors

HV-Model Based on Dual Polytope

Dual Polytope: $\mathcal{D}_{\mathcal{M}} = \{\mathbf{y} \in \mathbb{R}^3 | -1 \leq \mathbf{m}_n \mathbf{y} \leq 1, n = 1 \ldots N\}$



Dual polytope

Any quantum state is a mixture of vertices (HVs) of dual polytope

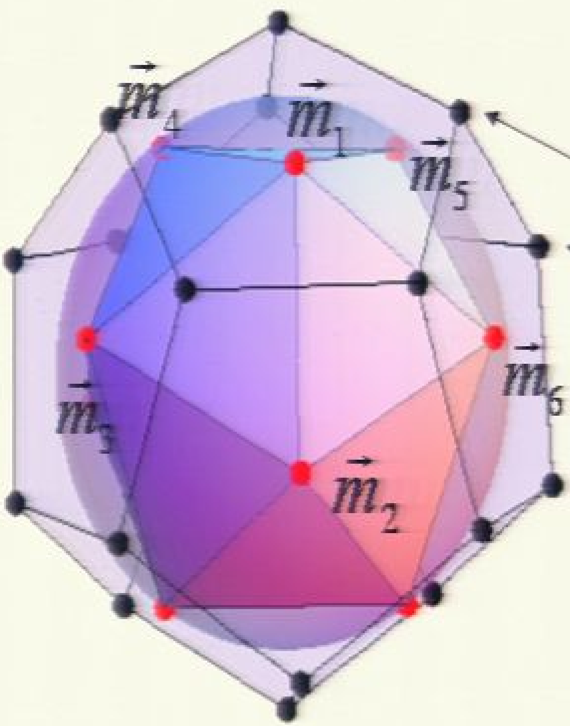
$$\vec{x} = \sum_i \alpha_i(\vec{x}) \vec{O}_i$$

can be **longer** than quantum Bloch vectors

$$0 \leq p_n(\vec{O}) \equiv \frac{1 \pm \vec{O} \cdot \vec{m}_n}{2} \leq 1$$

HV-Model Based on Dual Polytope

Dual Polytope: $\mathcal{D}_{\mathcal{M}} = \{\mathbf{y} \in \mathbb{R}^3 | -1 \le \mathbf{m}_n \mathbf{y} \le 1, n = 1 \ldots N\}$



Dual polytope

Any quantum state is a mixture of vertices (HVs) of dual polytope

$$\vec{x} = \sum_i \alpha_i(\vec{x}) \vec{O}_i$$

can be **longer** than quantum Bloch vectors

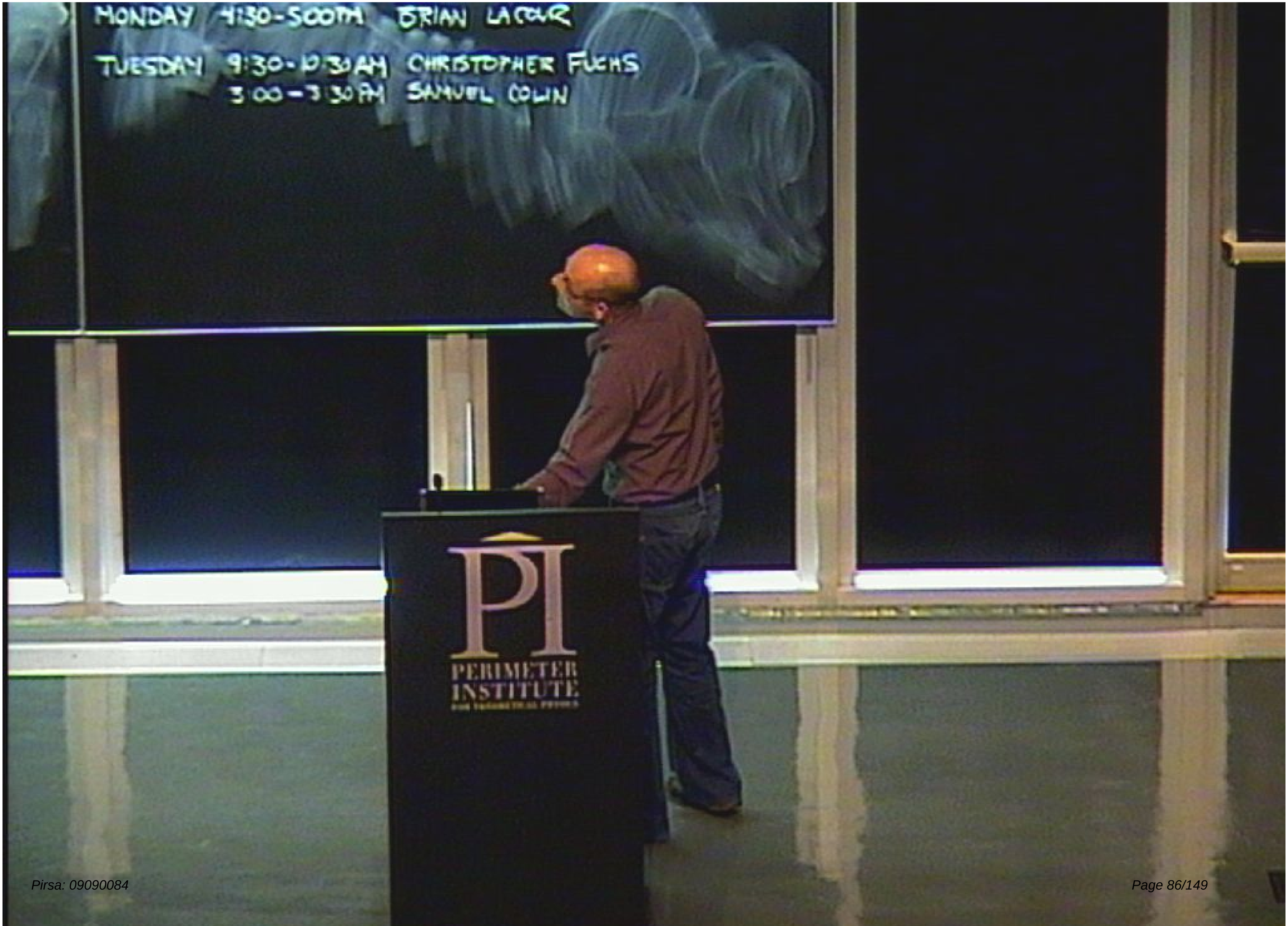
$$0 \le p_n(\vec{O}) \equiv \frac{1 \pm \vec{O} \cdot \vec{m}_n}{2} \le 1$$

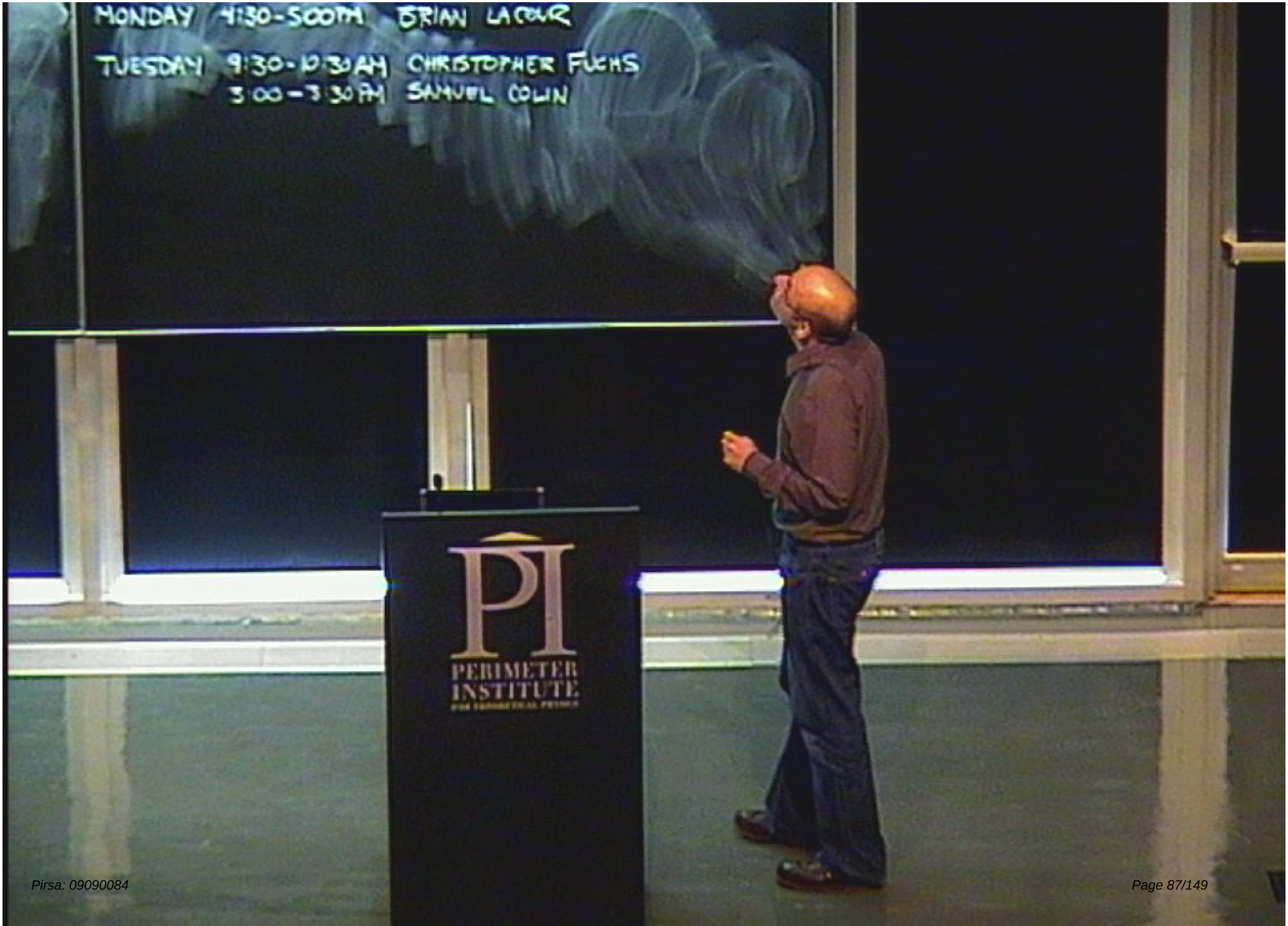
$$p_n(\vec{x}) = \sum_i \alpha_i(\vec{x}) \frac{1}{2}\left(1 + \vec{O}_i \cdot \vec{m}_n\right)$$

$$\sum_n p_n(\vec{x}) = 1$$

Measurement Polytope: Cube

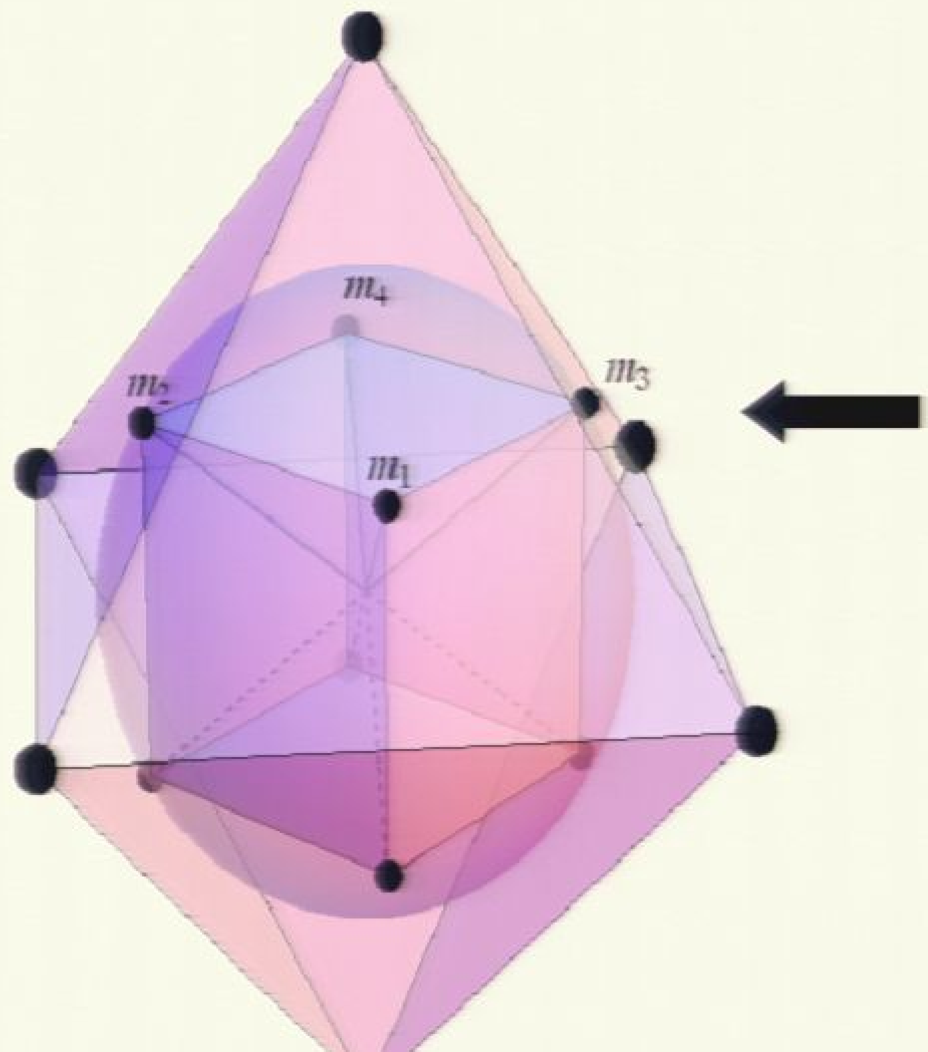
- N=4 measurement directions


MONDAY 4:30-5:00PM BRIAN LACOUR
TUESDAY 9:30-10:30AM CHRISTOPHER FUCHS
3:00-3:30PM SAMUEL COLIN
PI
PERIMETER
INSTITUTE


MONDAY 4:30-5:00PM BRIAN LACOUR
TUESDAY 9:30-10:30AM CHRISTOPHER FUCHS
3:00-3:30PM SAMUEL COLIN
PI
PERIMETER
INSTITUTE

Measurement Polytope: Cube

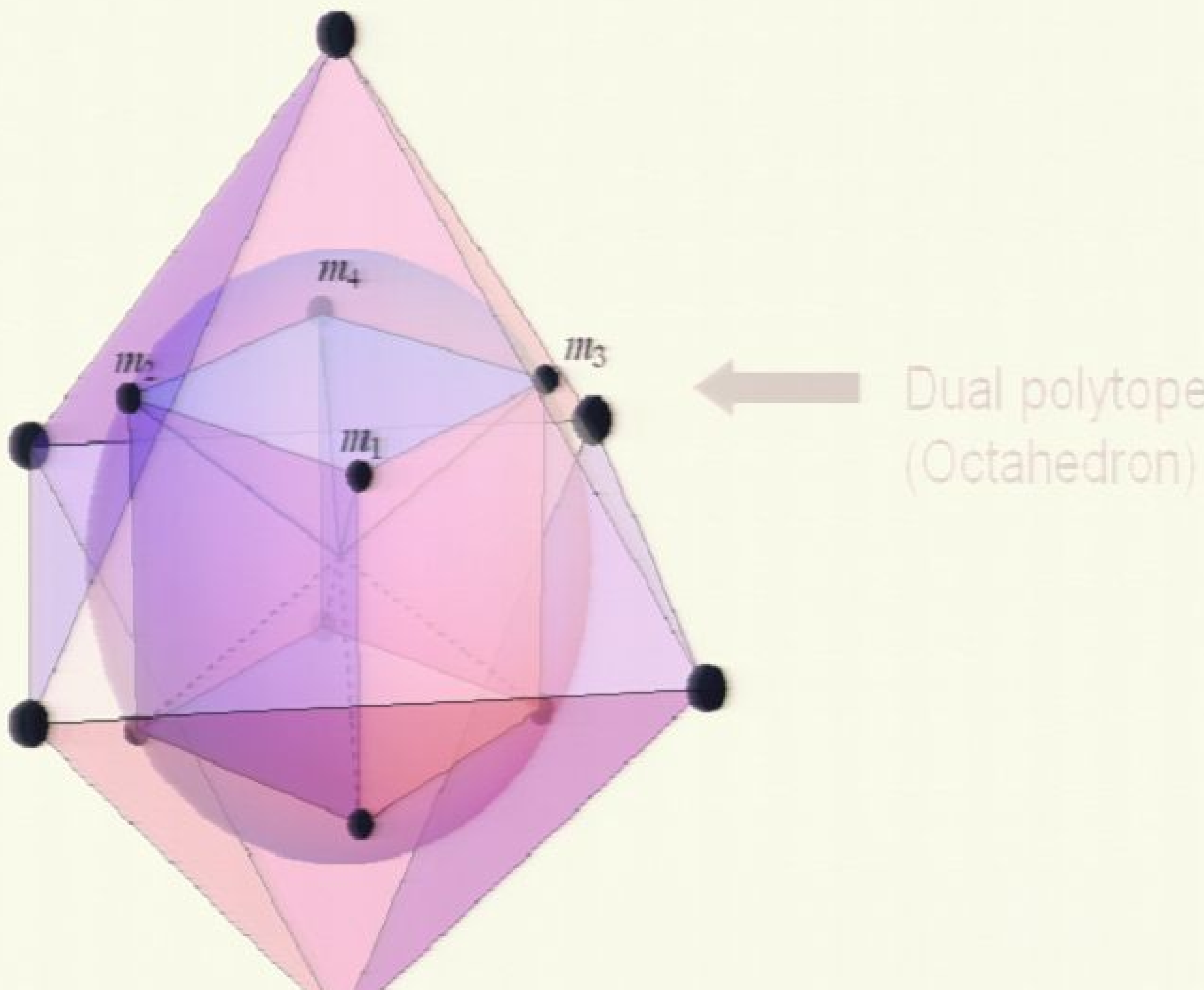
- N=4 measurement directions



Dual polytope (Octahedron)

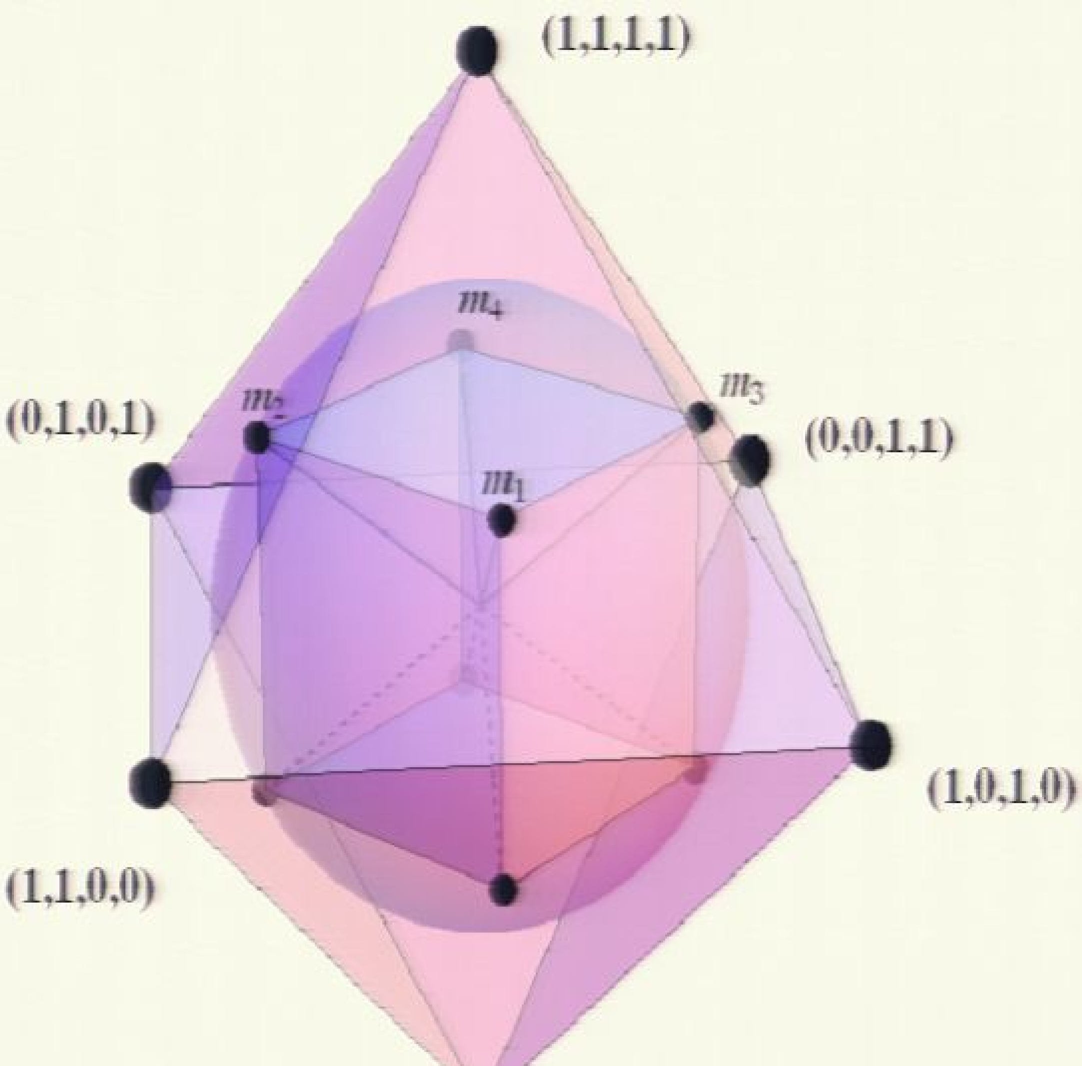
Measurement Polytope: Cube

- N=4 measurement directions



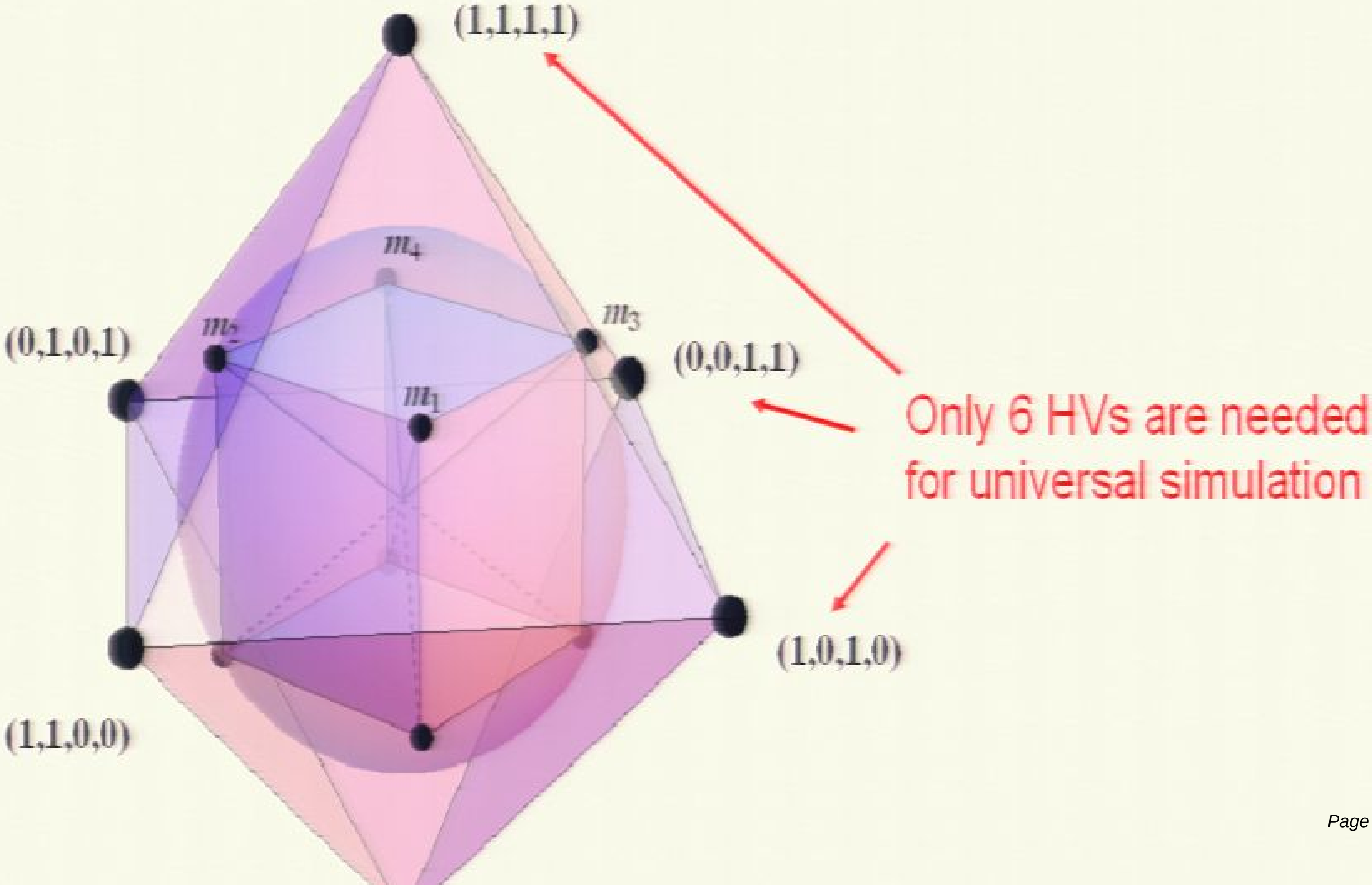
Measurement Polytope: Cube

- N=4 measurement directions

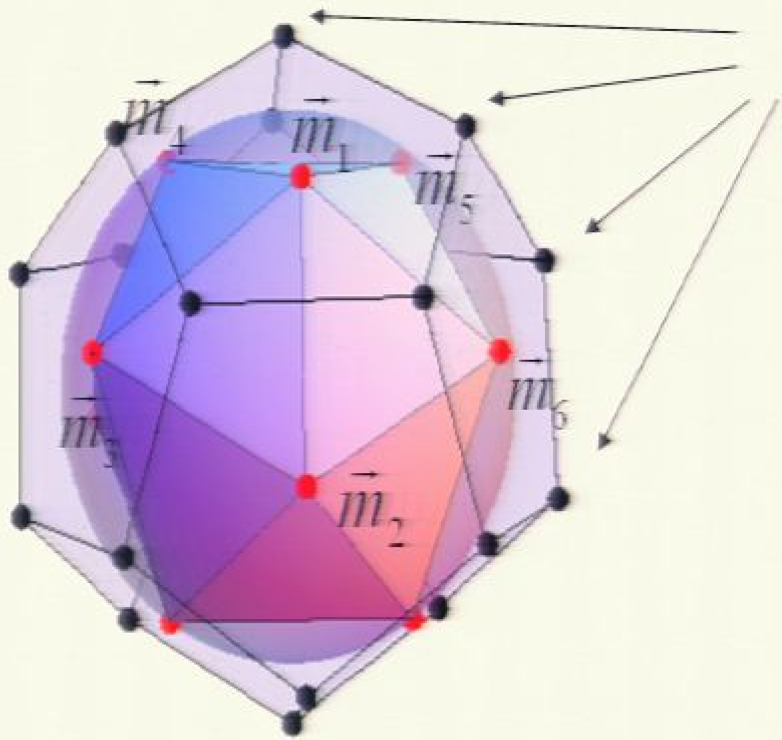


Measurement Polytope: Cube

- N=4 measurement directions

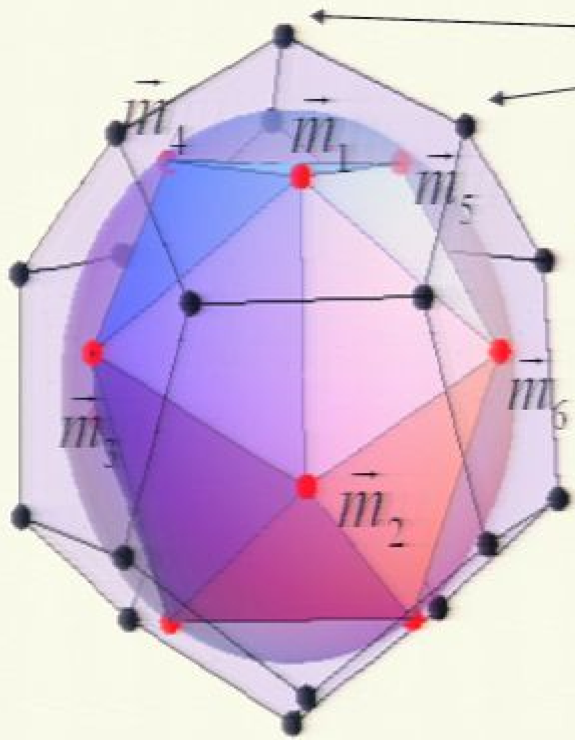


Lower and upper bound



F vertices of dual polytope

Lower and upper bound



F vertices of dual polytope

Caratheodory`s theorem

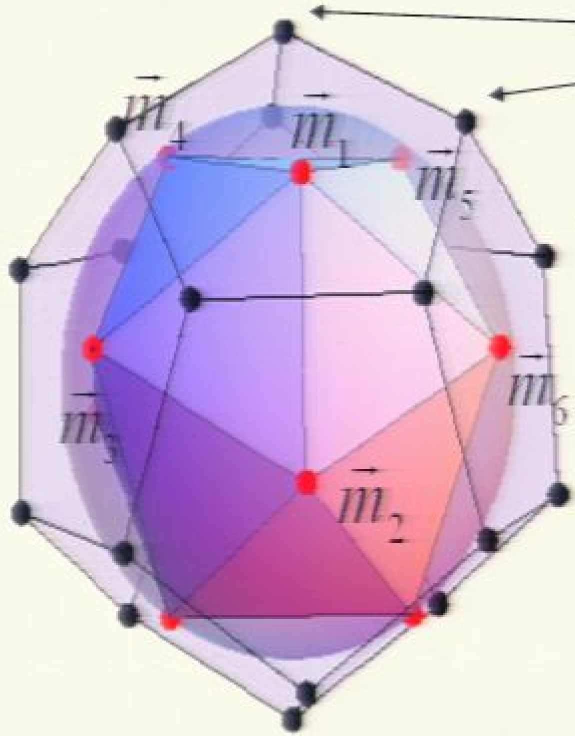
$$F \leq \Omega \leq (N-2)F$$

Probabilistic HV

Deterministic HV

***N* - 2** instead of ***N* + 1**: a vertex of the dual polytope saturates at least three of the inequalities defining the polytope

Lower and upper bound



F vertices of dual polytope

↓ Caratheodory`s theorem

$$F \leq \Omega \leq (N-2)F$$

Probabilistic HV ↗ ↖ Deterministic HV

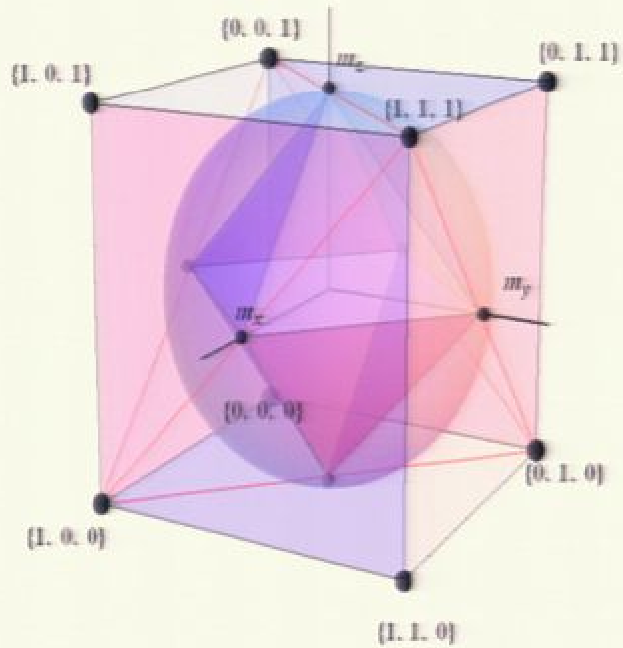
↓ Further analysis

$$N+1 \leq \Omega \leq 4(N-2)(N+1)$$

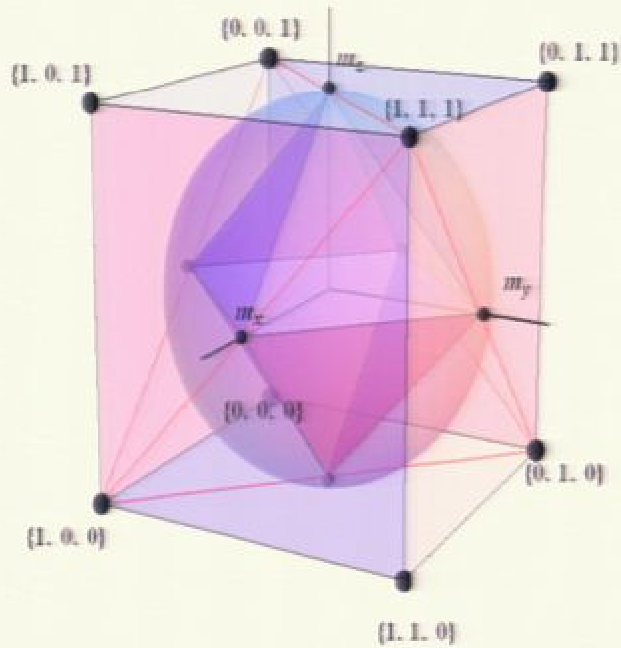
***N* - 2** instead of ***N* + 1**: a vertex of the dual polytope saturates at least three of the inequalities defining the polytope

P. McMullen, Mathematika 17, 179 (1970): A convex polytope with $2N$ vertices in $\mathbf{R}^3$, can have $N+1 \leq F \leq 4(N-1)$ facets

Symmetric Polytopes:

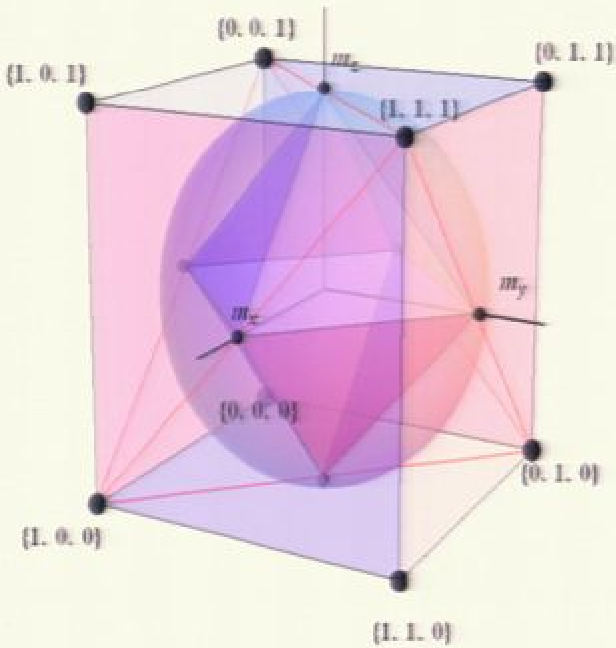


Symmetric Polytopes:

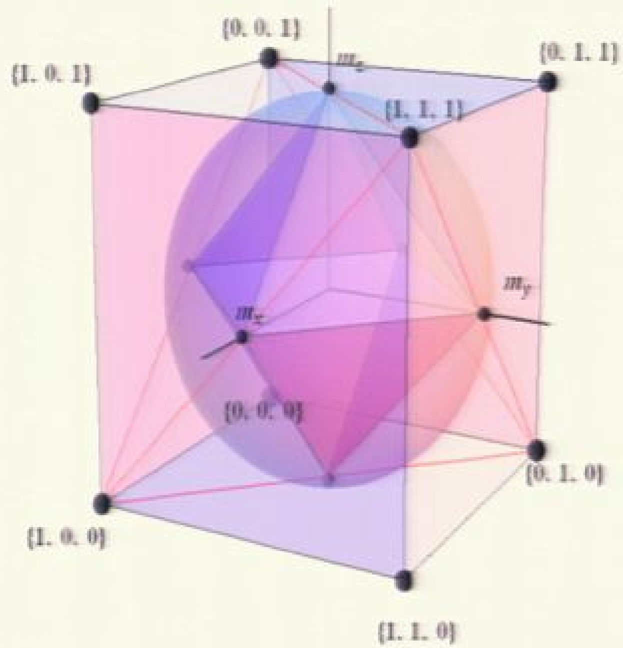


Measurement and Dual Polytope has the same (group) symmetry

Symmetric Polytopes:



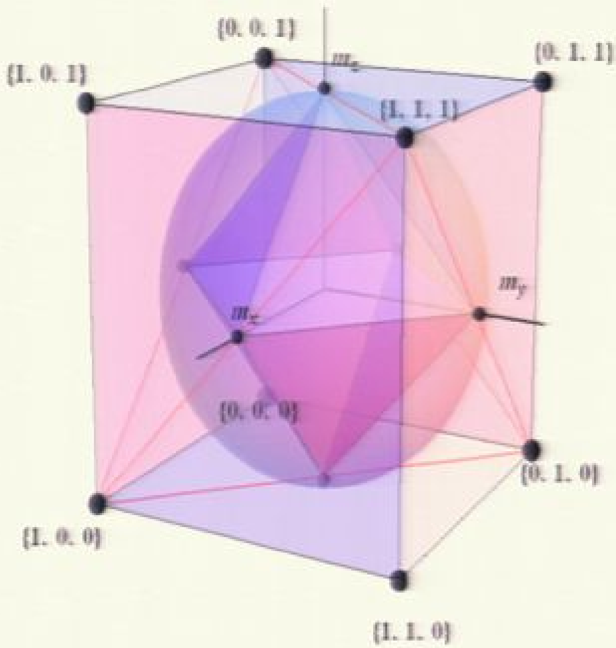
Symmetric Polytopes:



Measurement and Dual Polytope has the same (group) symmetry

Permutation representation $\mathbf{h}(g\mathbf{y}) = D_{\mathrm{P}}(g)\mathbf{h}(\mathbf{y})$

Symmetric Polytopes:



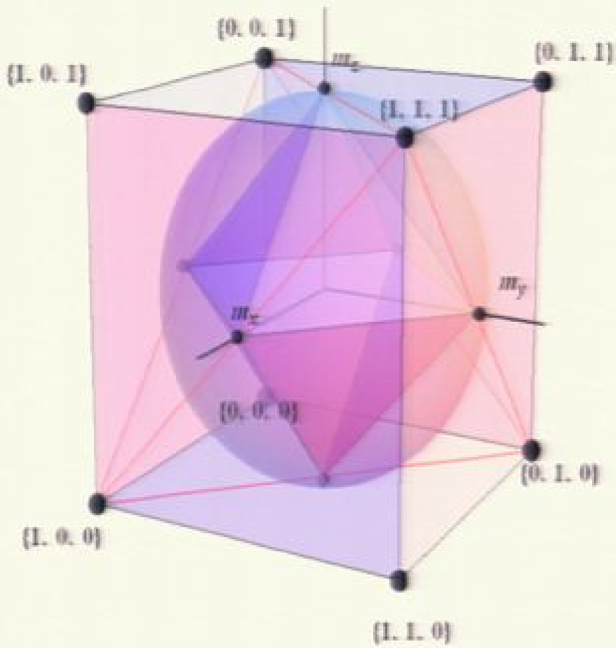
Measurement and Dual Polytope has the same (group) symmetry

HV associated to the vertex

vertex of the dual polytope

Permutation representation $\mathbf{h}(g\mathbf{y}) = D_{\mathrm{P}}(g)\mathbf{h}(\mathbf{y})$

Symmetric Polytopes:



Measurement and Dual Polytope has the same (group) symmetry

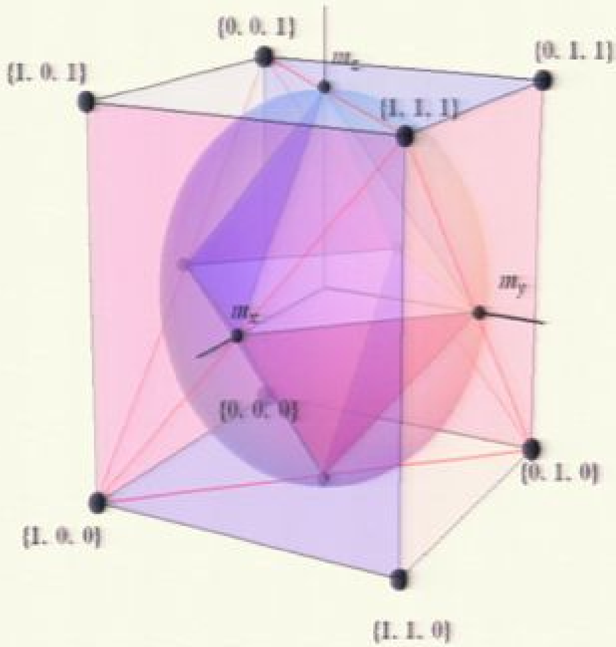
HV associated to the vertex

vertex of the dual polytope

Permutation representation $\mathbf{h}(g\mathbf{y}) = D_{\mathrm{P}}(g)\mathbf{h}(\mathbf{y})$

Decomposition in deterministic HVs: $\mathbf{h}(g\mathbf{y}) = \sum_l \alpha_l D_{\mathrm{P}}(g)\mathbf{O}_l$

Symmetric Polytopes:



Measurement and Dual Polytope has the same (group) symmetry

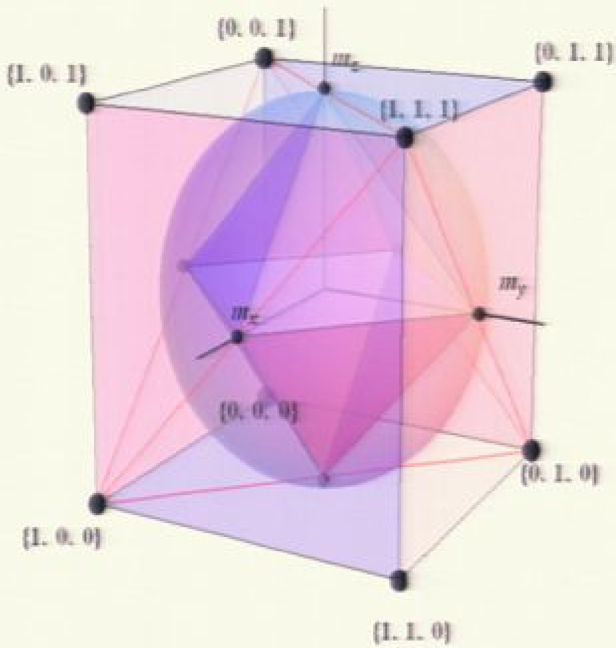
HV associated to the vertex → vertex of the dual polytope

Permutation representation $\mathbf{h}(g\mathbf{y}) = D_{\mathrm{P}}(g)\mathbf{h}(\mathbf{y})$

Decomposition in deterministic HVs: $\mathbf{h}(g\mathbf{y}) = \sum_l \alpha_l D_{\mathrm{P}}(g)\mathbf{O}_l$

Deterministic HVs = a union of group orbits $\{D_{\mathrm{P}}(g)\mathbf{O}_l | g \in G\}$

Symmetric Polytopes:



Measurement and Dual Polytope has the same (group) symmetry

HV associated to the vertex

vertex of the dual polytope

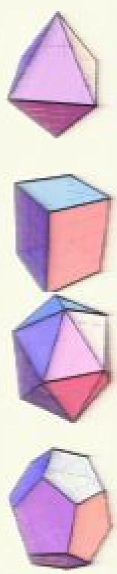
Permutation representation $\mathbf{h}(g\mathbf{y}) = D_{\mathrm{P}}(g)\mathbf{h}(\mathbf{y})$

Decomposition in deterministic HVs: $\mathbf{h}(g\mathbf{y}) = \sum_l \alpha_l D_{\mathrm{P}}(g)\mathbf{O}_l$

Deterministic HVs = a union of group orbits $\{D_{\mathrm{P}}(g)\mathbf{O}_l | g \in G\}$

Number of deterministic HVs cannot be smaller than

Platonic solids



Solid	N	2^N	Ω	
Octahedron	3	8	8	
Cube	4	16	6	
Icosahedron	6	64	20	Largest orbit
Dodecahedron	10	1024	24	Union of two lower orbits 12+12

Octahedron & Cube: Octahedral group, with 24 rotations

Icosahedron & Dodecahedron: Icosahedral group, with 60 rotations.

General Case: Qudit

Generalized Gell-Mann Operators

$$\hat{\rho} = \frac{1}{d}[\mathbb{1} + (d-1)\sum_{i=1}^{D} x_i \hat{\lambda}_i]$$

$$\mathrm{Tr}(\hat{\lambda}_i \hat{\lambda}_j) = \frac{d}{d-1}\delta_{ij}$$

$$D \equiv d^2 - 1$$

General Case: Qudit

Generalized Gell-Mann Operators

$$\hat{\rho} = \frac{1}{d}[\mathbb{1} + (d-1)\sum_{i=1}^{D} x_i \hat{\lambda}_i]$$

$$\mathrm{Tr}(\hat{\lambda}_i \hat{\lambda}_j) = \frac{d}{d-1}\delta_{ij}$$

$$D \equiv d^2 - 1$$

Quantum Probability

$$p_n(\vec{x}) = \frac{1}{d}\left(1 + (d-1)(\vec{x}\cdot\vec{m}_n)\right)$$

General Case: Qudit

Generalized Gell-Mann Operators

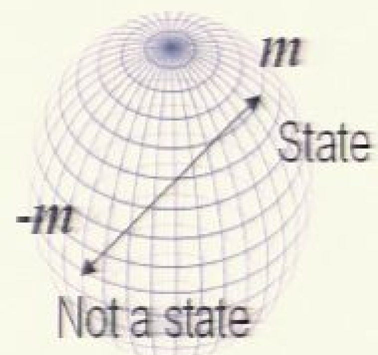
$$\hat{\rho} = \tfrac{1}{d}\left[\mathbb{1} + (d-1)\sum_{i=1}^{D} x_i \hat{\lambda}_i\right]$$

$$\mathrm{Tr}(\hat{\lambda}_i \hat{\lambda}_j) = \tfrac{d}{d-1}\,\delta_{ij}$$

$$D \equiv d^2 - 1$$

Quantum Probability

$$p_n(\vec{x}) = \frac{1}{d}\left(1 + (d-1)(\vec{x}\cdot\vec{m}_n)\right)$$



General Case: Qudit

Generalized Gell-Mann Operators

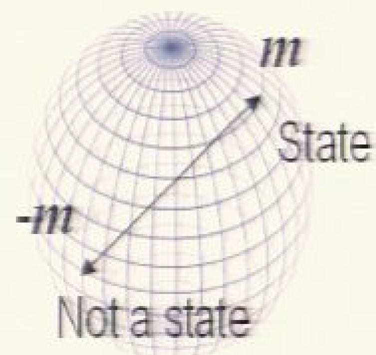
$$\hat{\rho} = \tfrac{1}{d}[\mathbb{1} + (d-1)\textstyle\sum_{i=1}^{D} x_i \hat{\lambda}_i]$$

$$\mathrm{Tr}(\hat{\lambda}_i \hat{\lambda}_j) = \tfrac{d}{d-1}\delta_{ij}$$

$$D \equiv d^2 - 1$$

Quantum Probability

$$p_n(\vec{x}) = \frac{1}{d}\left(1 + (d-1)(\vec{x}\cdot\vec{m}_n)\right)$$



Dual Polytope – *N* *d*-valued observables

$$\mathcal{P}_{\mathcal{M}} = \left\{\mathbf{y} \in \mathbb{R}^D \,|\, -\frac{1}{d-1} \le \mathbf{m}_n \mathbf{y} \le 1, n = 1, \ldots, dN\right\}.$$

General Case: Qudit

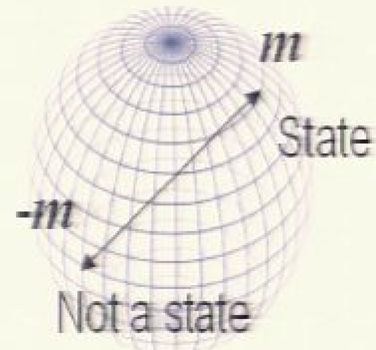
Generalized Gell-Mann Operators

$$\hat{\rho} = \tfrac{1}{d}\left[\mathbb{1} + (d-1)\sum_{i=1}^{D} x_i \hat{\lambda}_i\right] \qquad \mathrm{Tr}(\hat{\lambda}_i \hat{\lambda}_j) = \tfrac{d}{d-1}\delta_{ij}$$

$$D \equiv d^2 - 1$$

Quantum Probability

$$p_n(\vec{x}) = \frac{1}{d}\left(1 + (d-1)(\vec{x}\cdot\vec{m}_n)\right)$$



Dual Polytope – *N d*-valued observables

$$\mathcal{P}_{\mathcal{M}} = \left\{ \mathbf{y} \in \mathbb{R}^D \mid -\frac{1}{d-1} \leq \mathbf{m}_n \mathbf{y} \leq 1, n = 1, \ldots, dN \right\}.$$

Number of vertices *F*

Probabilistic HV: $\Omega = F \cong (2dN - \delta)^{D-\delta} \qquad \delta \equiv \lfloor (D+1)/2 \rfloor$

P. McMullen, Mathematika 17, 179 (1970)

General Case: Qudit

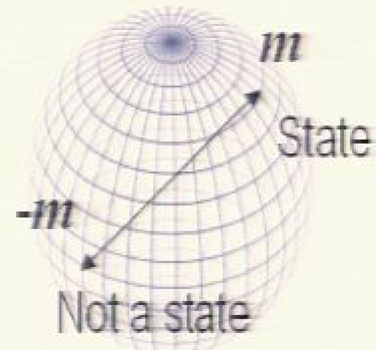
Generalized Gell-Mann Operators

$$\hat{\rho} = \tfrac{1}{d}[\mathbb{1} + (d-1)\sum_{i=1}^{D} x_i \hat{\lambda}_i] \qquad \mathrm{Tr}(\hat{\lambda}_i \hat{\lambda}_j) = \tfrac{d}{d-1}\delta_{ij}$$

$$D \equiv d^2 - 1$$

Quantum Probability

$$p_n(\vec{x}) = \frac{1}{d}\left(1 + (d-1)(\vec{x}\cdot\vec{m}_n)\right)$$



Dual Polytope – N d-valued observables

$$\mathcal{P}_{\mathcal{M}} = \left\{ \mathbf{y} \in \mathbb{R}^D \,|\, -\frac{1}{d-1} \le \mathbf{m}_n \mathbf{y} \le 1, n = 1, \ldots, dN \right\}.$$

Number of vertices F

Probabilistic HV: $\Omega = F \cong (2dN - \delta)^{D-\delta}$ $\qquad \delta \equiv \lfloor (D+1)/2 \rfloor$

Deterministic HV: $\Omega \cong (2dN - \delta)^{D-\delta} \cdot O(Nd)$

R. McMullen, Mathematika 17, 179 (1970) $\rightarrow$Poly(N)!

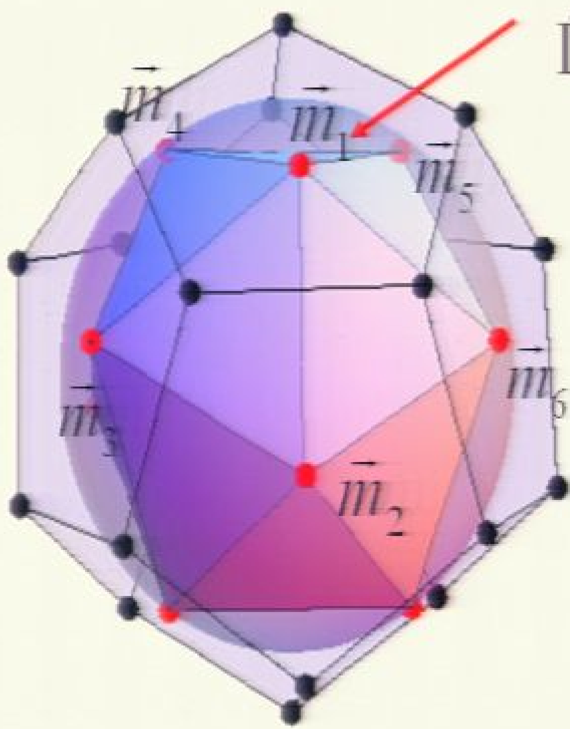
Limit of large number of measurements

(preparation- and measurement-universal model)

Hilbert-Schmidt Space of Hermitian operators with unit trace

Measurement Polytope

$\hat{\Pi}_n, \; n = 1, \ldots, dN$



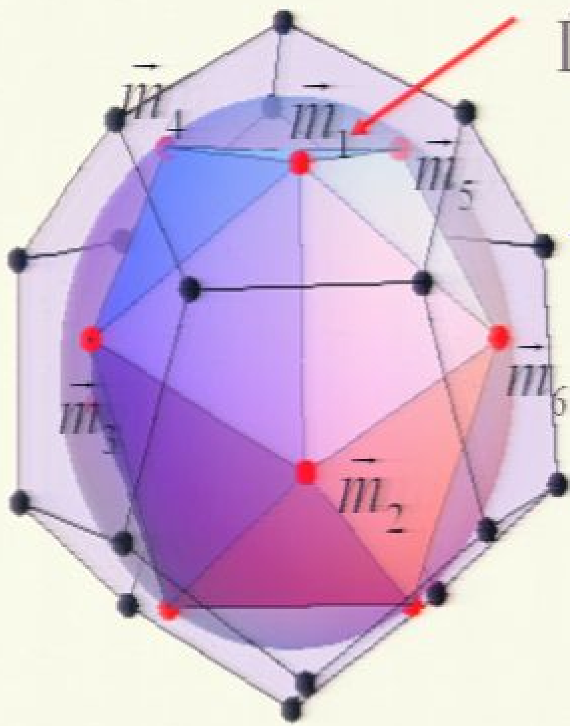
Limit of large number of measurements

(preparation- and measurement-universal model)

Hilbert-Schmidt Space of Hermitian operators with unit trace

Measurement Polytope

$\hat{\Pi}_n$. $n = 1, \ldots, dN$



Dual Polytope $\hat{y}_l$.

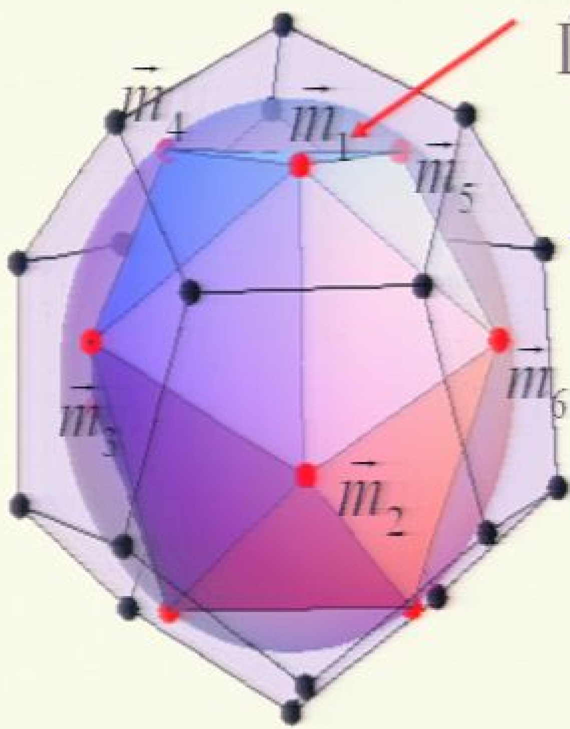
(larger than the set of quantum states)

$$\mathrm{Tr}(\hat{y}_l \hat{\Pi}_n) \in [0, 1]$$

Limit of large number of measurements

(preparation- and measurement-universal model)

Hilbert-Schmidt Space of Hermitian operators with unit trace



Measurement Polytope

$\hat{\Pi}_n.\ n = 1, \ldots, dN$

Dual Polytope $\hat{y}_l$.

(larger than the set of quantum states)

$$\mathrm{Tr}(\hat{y}_l \hat{\Pi}_n) \in [0, 1]$$

The limit N→∞

$$\mathrm{Tr}(\hat{y}_l \hat{\Pi}_n) \in [0, 1] \text{ for all } \hat{\Pi}_n.$$

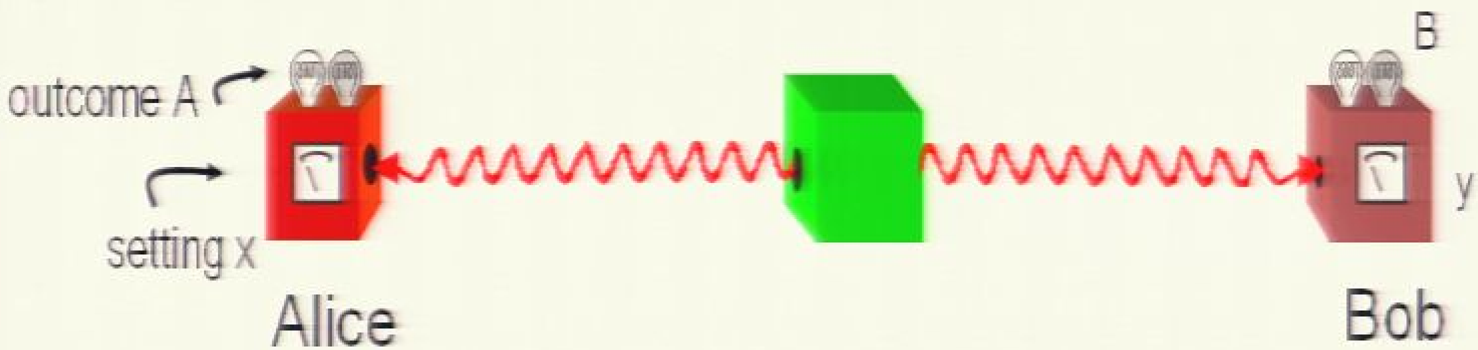
Eigenvalues between 0 and 1

$$\mathrm{Tr}(\hat{y}_l) = 1.$$

➡ $\hat{y}_l$ are quantum states

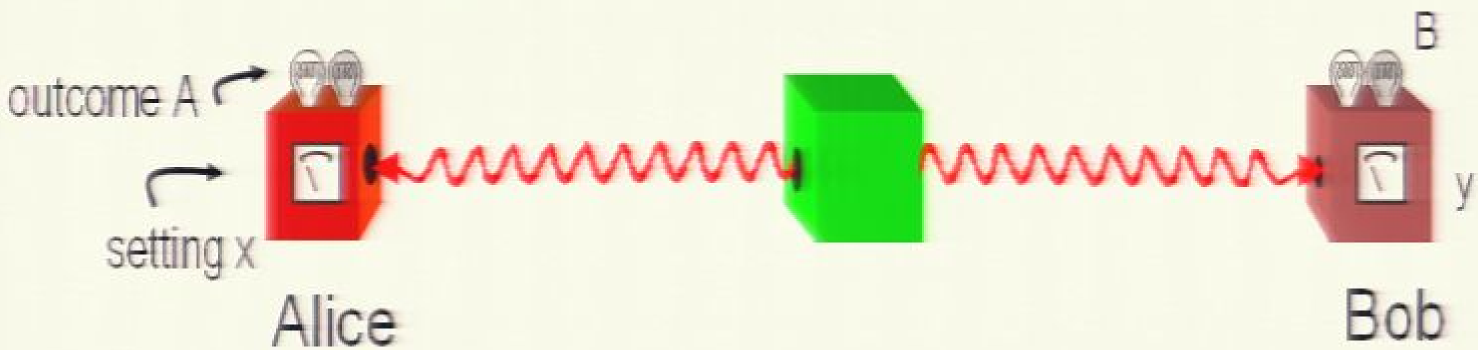
How "non-local" is non-local realism?

How "non-local" is non-local realism?



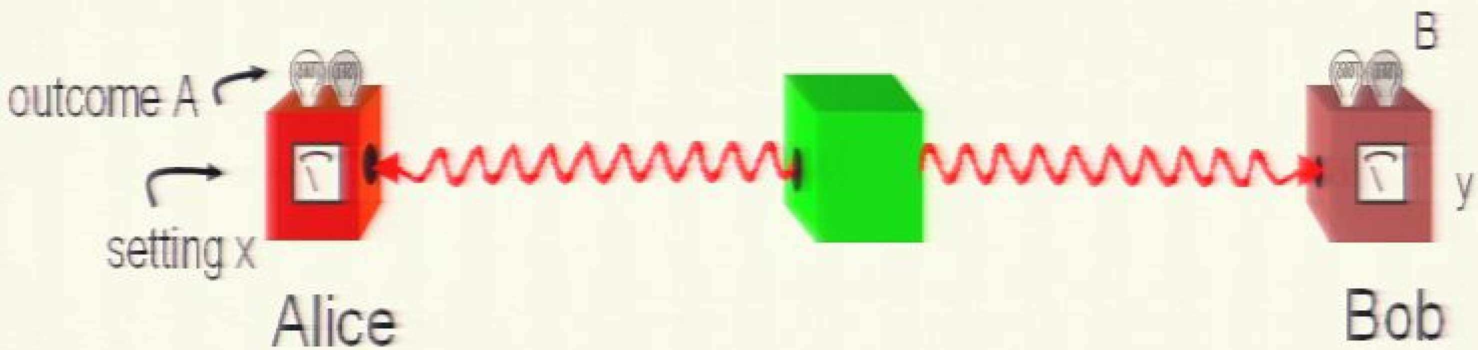
How "non-local" is non-local realism?

Alice (e.g. in the singlet case) cannot control the outcome, but can (freely) choose a seeting



How "non-local" is non-local realism?

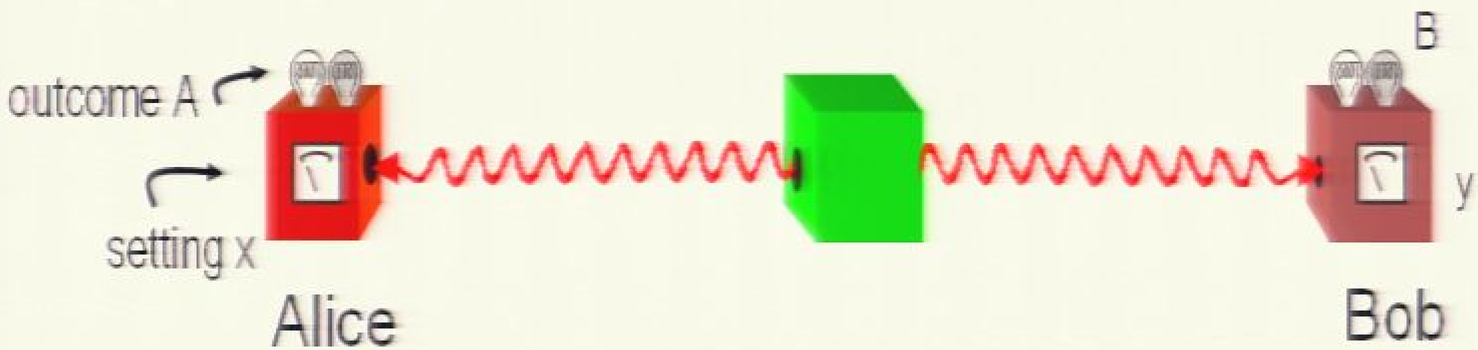
Alice (e.g. in the singlet case) cannot control the outcome, but can (freely) choose a seeting



No-signalling at the level of observables: $$P(B \mid x, y) = \sum_A P(A, B \mid x, y) = P(B \mid y)$$

How “non-local” is non-local realism?

Alice (e.g. in the singlet case) cannot control the outcome, but can (freely) choose a seeting



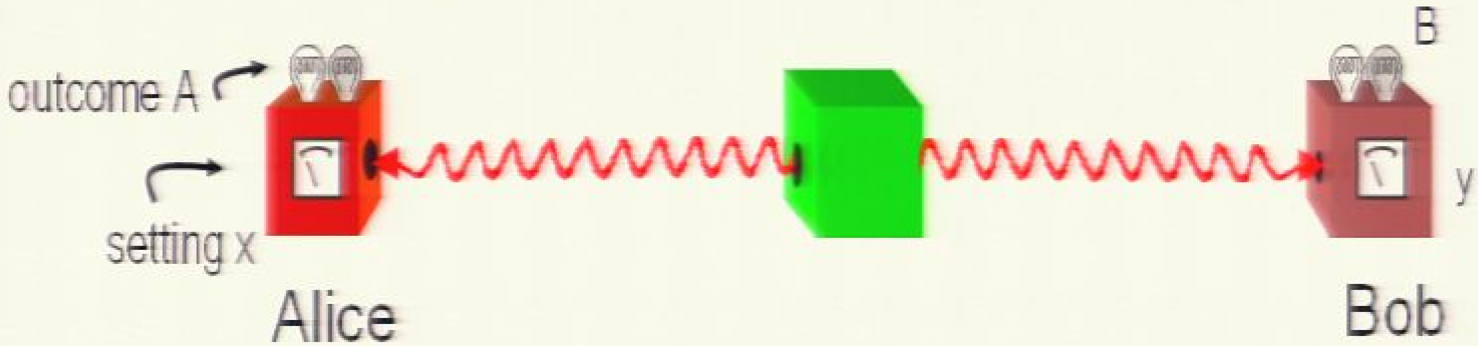
No-signalling at the level of observables:

$$P(B\,|\,x,y)=\sum_{A}P(A,B\,|\,x,y)=P(B\,|\,y)$$

But what if “hidden” probabilities exist and Bob has an access to them?

How "non-local" is non-local realism?

Alice (e.g. in the singlet case) cannot control the outcome, but can (freely) choose a seeting



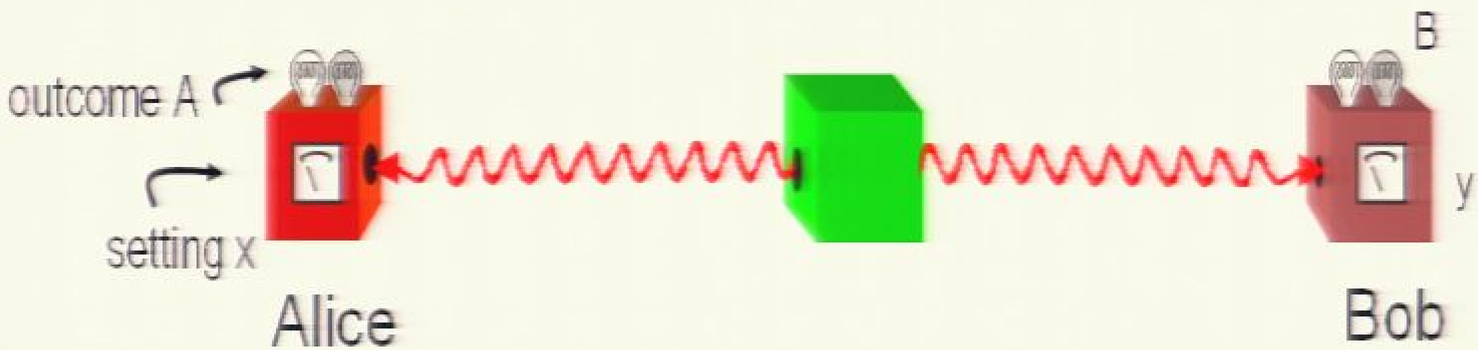
No-signalling at the level of observables: $$P(B \mid x, y) = \sum_A P(A, B \mid x, y) = P(B \mid y)$$

But what if "hidden" probabilities exist and Bob has an access to them?

No-signalling at the HV-level:

How "non-local" is non-local realism?

Alice (e.g. in the singlet case) cannot control the outcome, but can (freely) choose a seeting



No-signalling at the level of observables:

$$P(B\,|\,x,y) = \sum_A P(A,B\,|\,x,y) = P(B\,|\,y)$$

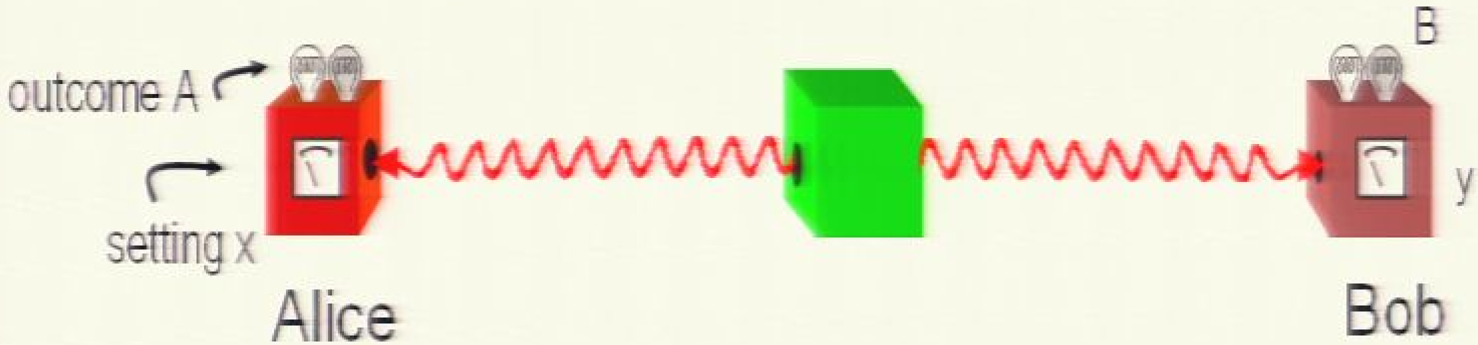
But what if "hidden" probabilities exist and Bob has an access to them?

No-signalling at the HV-level:

$$P_\lambda(B_1,B_2\,|\,x=1) = P_\lambda(B_1,B_2\,|\,x=2)$$

How "non-local" is non-local realism?

Alice (e.g. in the singlet case) cannot control the outcome, but can (freely) choose a seeting



No-signalling at the level of observables:

$$P(B\,|\,x,y)=\sum_A P(A,B\,|\,x,y)=P(B\,|\,y)$$

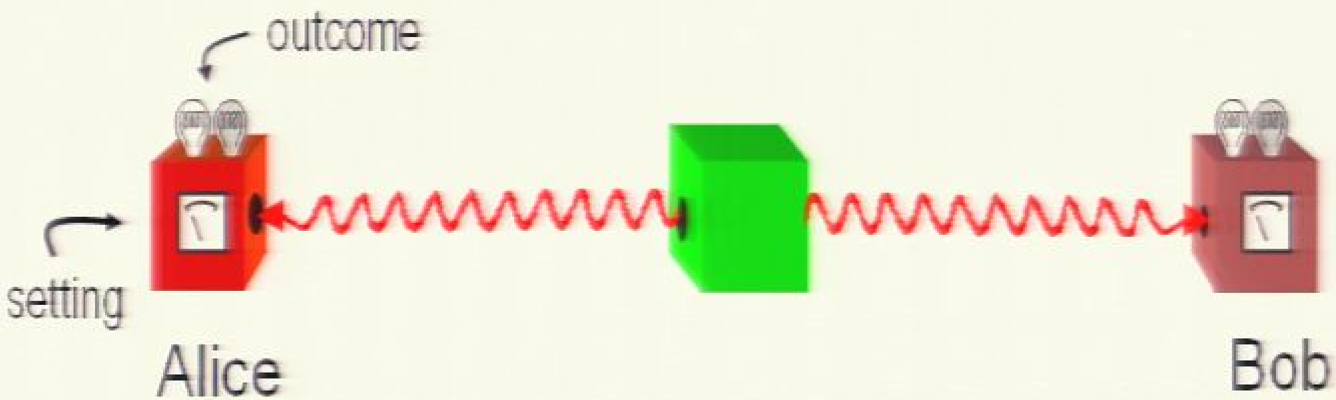
But what if "hidden" probabilities exist and Bob has an access to them?

No-signalling at the HV-level:

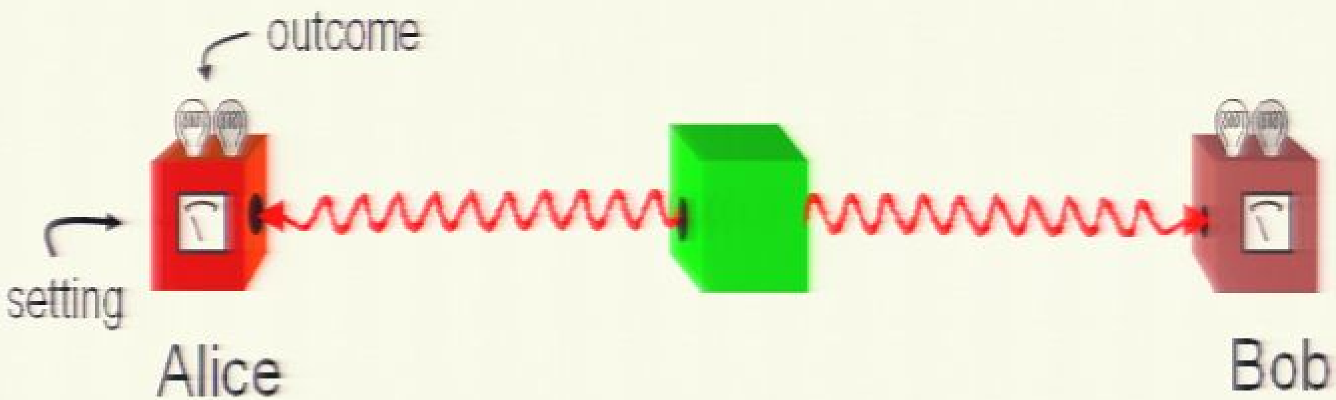
$$P_\lambda(B_1,B_2\,|\,x=1)=P_\lambda(B_1,B_2\,|\,x=2)$$

"Half-realism" (joint probability

Intuition

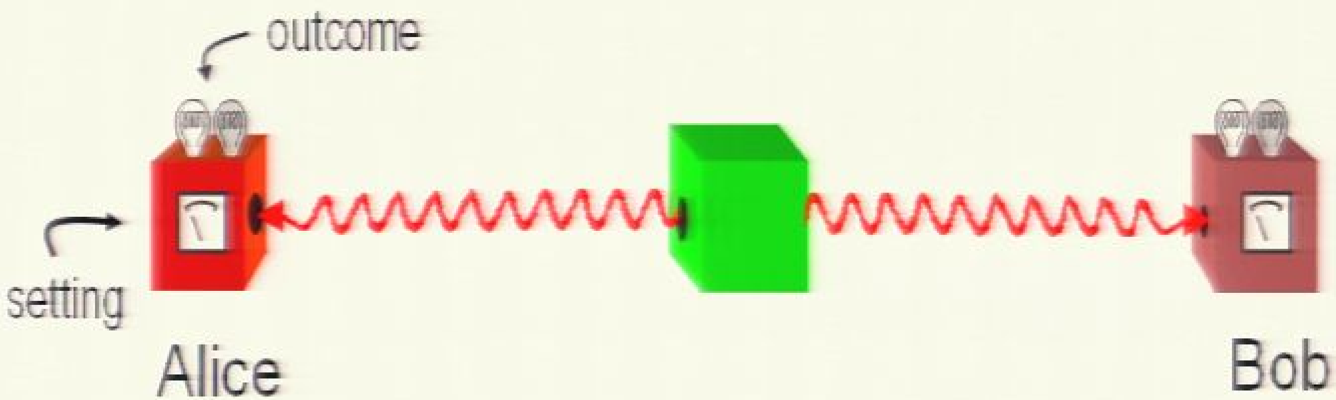


Intuition



Clauser-Horne-Shimony-Holt:

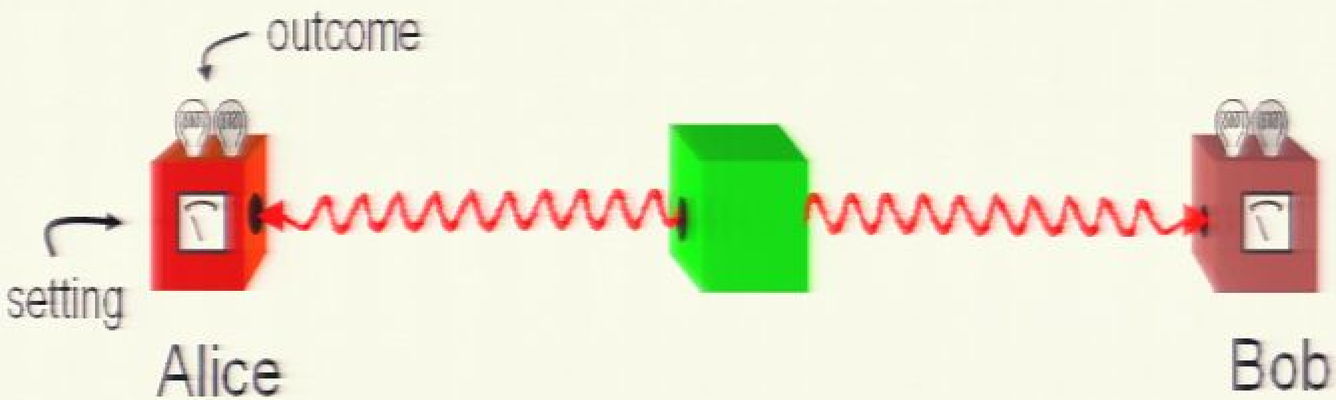
Intuition



Clauser-Horne-Shimony-Holt:

$$|E_{11}+E_{12}|+|E_{21}-E_{22}| \leq 2$$

Intuition

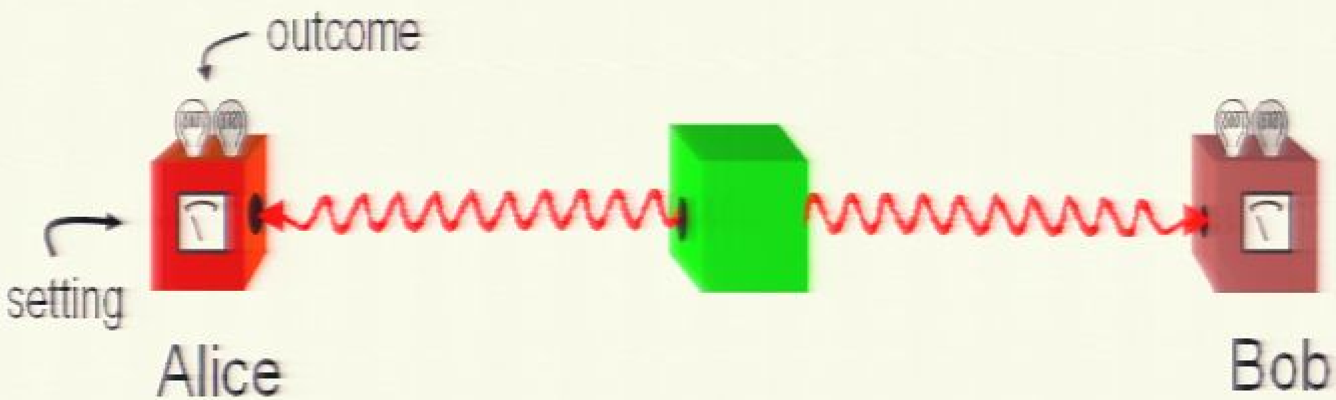


Clauser-Horne-Shimony-Holt:

$$|E_{11} + E_{12}| + |E_{21} - E_{22}| \leq 2$$

Logical Bound (4) if full info about A's setting from B's correlation

Intuition



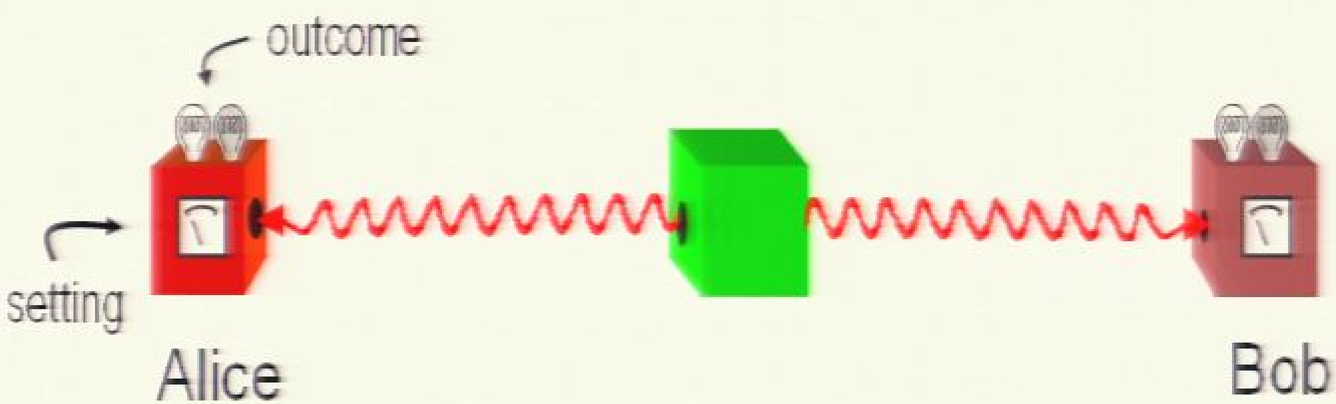
Clauser-Horne-Shimony-Holt:

$$|E_{11} + E_{12}| + |E_{21} - E_{22}| \leq 2$$

Logical Bound (4) if full info about A's setting from B's correlation

$$A_1 = B_1 = B_2; \quad A_2 = B_1 = -B_2$$

Intuition



Clauser-Horne-Shimony-Holt:

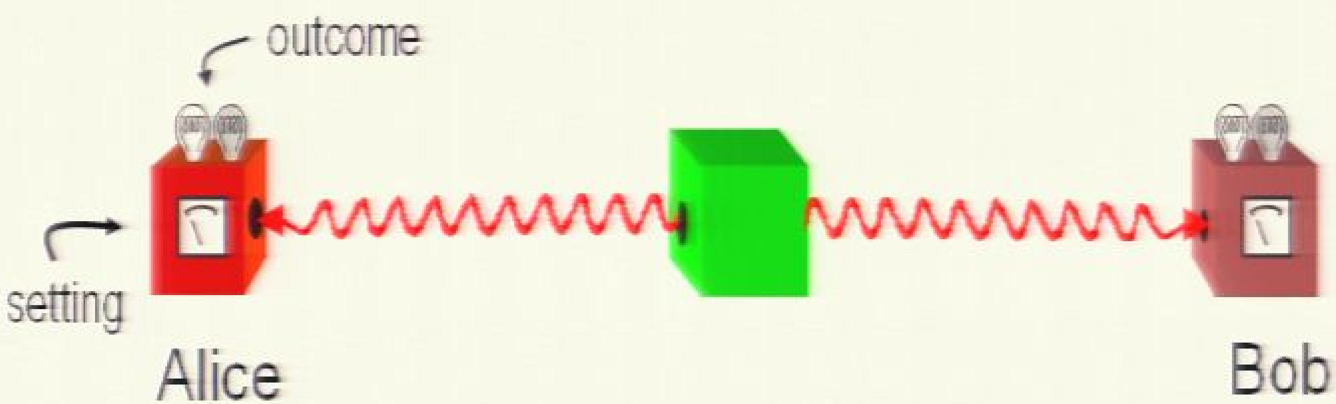
$$|E_{11} + E_{12}| + |E_{21} - E_{22}| \leq 2$$

Logical Bound (4) if full info about A's setting from B's correlation

$$A_1 = B_1 = B_2; \quad A_2 = B_1 = -B_2$$

No-signalling at
the HV-level.

Intuition



Clauser-Horne-Shimony-Holt:

$$|E_{11}+E_{12}|+|E_{21}-E_{22}| \quad \leq 2$$

Logical Bound (4) if full info about A's setting from B's correlation

$$A_1 = B_1 = B_2; \quad A_2 = B_1 = -B_2$$

No-signalling at the HV-level.

$$P_\lambda(B_1 = B_2 \mid x=1) = P_\lambda(B_1 = B_2 \mid x=2)$$

$$\Rightarrow P_\lambda(A_1B_1 = A_1B_2) = P_\lambda(A_2B_1 = A_2B_2)$$

Proof: Bell's violation implies signalling at the HV level

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b|=ab=1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}|\leq\overline{ab}\leq 1-|\bar{a}-\bar{b}|$$

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b| = ab = 1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}| \leq \overline{ab} \leq 1-|\bar{a}-\bar{b}|$$

$$a \equiv A_x B_1; \;\; b \equiv A_x B_2$$

$$\Rightarrow -1+|E_{x1}+E_{x2}| \leq \overline{A_x B_1 A_x B_2} \leq 1-|E_{x1}-E_{x2}| \quad (*)$$

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b|=ab=1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}|\le\overline{ab}\le 1-|\bar{a}-\bar{b}|$$

$$a\equiv A_x B_1;\ \ b\equiv A_x B_2$$

$$\Rightarrow -1+|E_{x1}+E_{x2}|\le\overline{A_x B_1 A_x B_2}\le 1-|E_{x1}-E_{x2}| \quad (*)$$

"Correlations between correlations":

$$P(A_x B_1 = A_x B_2) - P(A_x B_1 = -A_x B_2) =$$

$$2P(A_x B_1 = A_x B_2) - 1 \equiv \varepsilon_x$$

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b|=ab=1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}|\leq \overline{ab}\leq 1-|\bar{a}-\bar{b}|$$

$$a\equiv A_x B_1;\;\; b\equiv A_x B_2$$

$$\Rightarrow -1+|E_{x1}+E_{x2}|\leq \overline{A_x B_1 A_x B_2}\leq 1-|E_{x1}-E_{x2}| \quad (*)$$

"Correlations between correlations":

$$P(A_x B_1 = A_x B_2)-P(A_x B_1 = -A_x B_2)=$$
$$2P(A_x B_1 = A_x B_2)-1\equiv \varepsilon_x$$

Right-hand side of (*) $\quad \varepsilon_1 \leq 1-|E_{11}-E_{12}|$

Left-hand side of (*) $\quad -\varepsilon_2 \leq 1-|E_{21}+E_{22}|$

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b|=ab=1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}|\leq \overline{ab}\leq 1-|\bar{a}-\bar{b}|$$

$$a\equiv A_xB_1;\;\; b\equiv A_xB_2$$

$$\Rightarrow -1+|E_{x1}+E_{x2}|\leq \overline{A_xB_1A_xB_2}\leq 1-|E_{x1}-E_{x2}| \quad (*)$$

"Correlations between correlations":

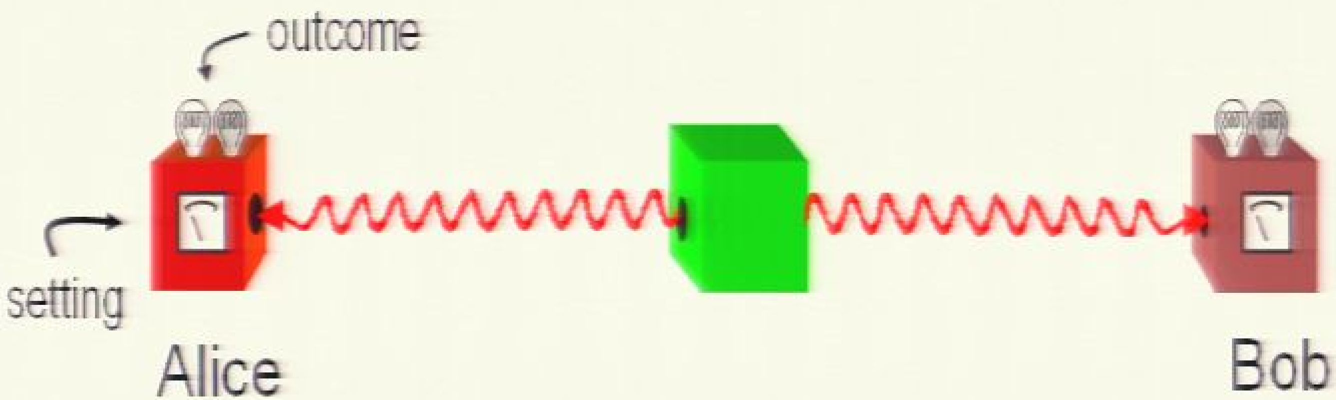
$$P(A_xB_1=A_xB_2)-P(A_xB_1=-A_xB_2)=$$
$$2P(A_xB_1=A_xB_2)-1\equiv \varepsilon_x$$

Right-hand side of (*) $\varepsilon_1\leq 1-|E_{11}-E_{12}|$

Left-hand side of (*) $-\varepsilon_2\leq 1-|E_{21}+E_{22}|$

No-signalling at the HV-level $\varepsilon_1-\varepsilon_2=0$

Intuition



Clauser-Horne-Shimony-Holt:

$$|E_{11} + E_{12}| + |E_{21} - E_{22}| \quad \leq 2$$

Logical Bound (4) if full info about A's setting from B's correlation

$$A_1 = B_1 = B_2; \quad A_2 = B_1 = -B_2$$

No-signalling at the HV-level.

$$P_\lambda(B_1 = B_2 \mid x = 1) = P_\lambda(B_1 = B_2 \mid x = 2)$$

$$\Rightarrow P_\lambda(A_1 B_1 = A_1 B_2) = P_\lambda(A_2 B_1 = A_2 B_2)$$

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b|=ab=1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}|\le \overline{ab}\le 1-|\bar{a}-\bar{b}|$$

$$a\equiv A_x B_1;\;\; b\equiv A_x B_2$$

$$\Rightarrow -1+|E_{x1}+E_{x2}|\le \overline{A_x B_1 A_x B_2}\le 1-|E_{x1}-E_{x2}| \quad (*)$$

"Correlations between correlations":

$$P(A_x B_1 = A_x B_2) - P(A_x B_1 = -A_x B_2) =$$
$$2P(A_x B_1 = A_x B_2) - 1 \equiv \varepsilon_x$$

Right-hand side of (*) $\varepsilon_1 \le 1-|E_{11}-E_{12}|$

Left-hand side of (*) $-\varepsilon_2 \le 1-|E_{21}+E_{22}|$

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b|=ab=1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}|\leq \overline{ab}\leq 1-|\bar{a}-\bar{b}|$$

$$a\equiv A_x B_1;\;\; b\equiv A_x B_2$$

$$\Rightarrow -1+|E_{x1}+E_{x2}|\leq \overline{A_x B_1 A_x B_2}\leq 1-|E_{x1}-E_{x2}| \quad (*)$$

"Correlations between correlations":

$$P(A_x B_1 = A_x B_2) - P(A_x B_1 = -A_x B_2) =$$
$$2P(A_x B_1 = A_x B_2) - 1 \equiv \varepsilon_x$$

Right-hand side of (*) $\quad \varepsilon_1 \leq 1-|E_{11}-E_{12}|$

Left-hand side of (*) $\quad -\varepsilon_2 \leq 1-|E_{21}+E_{22}|$

No-signalling at the HV-level $\quad \varepsilon_1 - \varepsilon_2 = 0$

Proof: Bell's violation implies signalling at the HV level

$$-1+|a+b| = ab = 1-|a-b|$$

$$\Rightarrow -1+|\bar{a}+\bar{b}| \le \overline{ab} \le 1-|\bar{a}-\bar{b}|$$

$$a \equiv A_x B_1; \;\; b \equiv A_x B_2$$

$$\Rightarrow -1+|E_{x1}+E_{x2}| \le \overline{A_x B_1 A_x B_2} \le 1-|E_{x1}-E_{x2}| \quad (*)$$

"Correlations between correlations":

$$P(A_x B_1 = A_x B_2) - P(A_x B_1 = -A_x B_2) =$$

$$2P(A_x B_1 = A_x B_2) - 1 \equiv \varepsilon_x$$

Right-hand side of (*) $\quad \varepsilon_1 \le 1-|E_{11}-E_{12}|$

Left-hand side of (*) $\quad -\varepsilon_2 \le 1-|E_{21}+E_{22}|$

No-signalling at the HV-level $\quad \varepsilon_1 - \varepsilon_2 = 0 \longrightarrow |E_{11}+E_{12}| + |E_{21}-E_{22}| \le 2$

Summary:

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

2. Quantum mechanics is an optimal description in the limit. Even for a single qubit, "realism" as HV program is extremely resource demanding, requiring infinitely many HV states.

Reference:

B. Dakic, M. Šuvakov, T. Paterek, and Č. Brukner
Phys. Rev. Lett. **101**, 190402 (2008)

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

2. Quantum mechanics is an optimal description in the limit. Even for a single qubit, “realism” as HV program is extremely resource demanding, requiring infinitely many HV states.

   Reference:
   B. Dakic, M. Šuvakov, T. Paterek, and Č. Brukner
   Phys. Rev. Lett. **101**, 190402 (2008)

3. Any HV theory violating Bell’s inequality allows superluminal signalling at the HV level.

   Reference:
   M. Pawlowski, J. Kofler, T. Paterek, Č. Brukner

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

2. Quantum mechanics is an optimal description in the limit. Even for a single qubit, "realism" as HV program is extremely resource demanding, requiring infinitely many HV states.

Reference:

B. Dakic, M. Šuvakov, T. Paterek, and Č. Brukner
Phys. Rev. Lett. **101**, 190402 (2008)

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

2. Quantum mechanics is an optimal description in the limit. Even for a single qubit, "realism" as HV program is extremely resource demanding, requiring infinitely many HV states.

   Reference:
   B. Dakic, M. Šuvakov, T. Paterek, and Č. Brukner
   Phys. Rev. Lett. **101**, 190402 (2008)

3. Any HV theory violating Bell's inequality allows superluminal signalling at the HV level.

   Reference:
   M. Pawlowski, J. Kofler, T. Paterek, Č. Brukner

Pauli to Born (1954)

[1933] PAULI AN BORN

[Zürich, Anfang Dezember 1954]
[Fragment][1]

Entgegen allen rückschrittlichen Bemühungen (Bohm, Schrödinger usw. und im gewissen Sinne auch Einstein) bin ich gewiß, daß der statistische Charakter der ψ-Funktion und damit der Naturgesetze – auf dem Sie von Anfang an gegen Schrödingers Widerstand bestanden haben – den Stil der Gesetze wenigstens für einige Jahrhunderte bestimmen wird. Es mag sein, daß man später, z.B. im Zusammenhang mit den Lebensvorgängen, etwas ganz Neues finden wird, aber von einem Weg zurück zu träumen, zurück zum klassischen Stil von Newton-Maxwell (und es sind nur Träume, denen sich diese Herren hingeben) scheint mir hoffnungslos, abwegig, schlechter Geschmack. Und, könnten wir hinzufügen, es ist nicht einmal ein schöner Traum.

Against all the retrogressive endeavors (Bohm, Schrödinger etc. and in some sense also Einstein) I am sure that the statistical character of the Ψ-function und hence of nature's laws -- on which you insisted from the very beginning against Schrödinger's resistance -- will define the style of the laws at least for some centuries. It may be that later, e.g. in connection with the living processes, one will find something entirely new, but to dream of a way back, back to the classical style of Newton-Maxwell (and these are just dreams which these gentlemen are giving themselves up to) seems to me hopeless, groundless, bad taste. And, we could add, it is not even a beautiful dream.

Moral ...

The theory has been telling us for 74 years that there is a problem with naive realism.

Why not take the message?

Pauli to Born (1954)

[1933] PAULI AN BORN

[Zürich, Anfang Dezember 1954]
[Fragment][1]

Entgegen allen rückschrittlichen Bemühungen (Bohm, Schrödinger usw. und im gewissen Sinne auch Einstein) bin ich gewiß, daß der statistische Charakter der ψ-Funktion und damit der Naturgesetze – auf dem Sie von Anfang an gegen Schrödingers Widerstand bestanden haben – den Stil der Gesetze wenigstens für einige Jahrhunderte bestimmen wird. Es mag sein, daß man später, z.B. im Zusammenhang mit den Lebensvorgängen, etwas ganz Neues finden wird, aber von einem Weg zurück zu träumen, zurück zum klassischen Stil von Newton-Maxwell (und es sind nur Träume, denen sich diese Herren hingeben) scheint mir hoffnungslos, abwegig, schlechter Geschmack. Und, könnten wir hinzufügen, es ist nicht einmal ein schöner Traum.

Against all the retrogressive endeavors (Bohm, Schrödinger etc. and in some sense also Einstein) I am sure that the statistical character of the Ψ-function und hence of nature's laws -- on which you insisted from the very beginning against Schrödinger's resistance -- will define the style of the laws at least for some centuries. It may be that later, e.g. in connection with the living processes, one will find something entirely new, but to dream of a way back, back to the classical style of Newton-Maxwell (and these are just dreams which these gentlemen are giving themselves up to) seems to me hopeless, groundless, bad taste. And, we could add, it is not even a beautiful dream.

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

2. Quantum mechanics is an optimal description in the limit. Even for a single qubit, "realism" as HV program is extremely resource demanding, requiring infinitely many HV states.

Reference:

B. Dakic, M. Šuvakov, T. Paterek, and Č. Brukner
Phys. Rev. Lett. **101**, 190402 (2008)

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

2. Quantum mechanics is an optimal description in the limit. Even for a single qubit, "realism" as HV program is extremely resource demanding, requiring infinitely many HV states.

   Reference:
   B. Dakic, M. Šuvakov, T. Paterek, and Č. Brukner
   Phys. Rev. Lett. **101**, 190402 (2008)

3. Any HV theory violating Bell's inequality allows superluminal signalling at the HV level.

   Reference:
   M. Pawlowski, J. Kofler, T. Paterek, Č. Brukner

Summary:

1. At most poly(N) HVs are enough to simulate N measurements on an arbitrary qudit.

2. Quantum mechanics is an optimal description in the limit. Even for a single qubit, "realism" as HV program is extremely resource demanding, requiring infinitely many HV states.

   Reference:
   B. Dakic, M. Šuvakov, T. Paterek, and Č. Brukner
   Phys. Rev. Lett. **101**, 190402 (2008)

3. Any HV theory violating Bell's inequality allows superluminal signalling at the HV level.

   Reference:
   M. Pawlowski, J. Kofler, T. Paterek, Č. Brukner